

Global Heat Kernel Estimates for $\Delta + \Delta^{\alpha/2}$ in Half-space-like Domains

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Abstract

Suppose that $d \geq 1$ and $\alpha \in (0, 2)$. In this paper, by using probabilistic methods, we establish sharp two-sided pointwise estimates for the Dirichlet heat kernels of $\{\Delta + a^\alpha \Delta^{\alpha/2}; a \in (0, 1]\}$ on half-space-like $C^{1,1}$ domains for all time $t > 0$. The large time estimates for half-space-like domains are very different from those for bounded domains. Our estimates are uniform in $a \in (0, 1]$ in the sense that the constants in the estimates are independent of $a \in (0, 1]$. Thus it yields the Dirichlet heat kernel estimates for Brownian motion in half-space-like domains by taking $a \rightarrow 0$. Integrating the heat kernel estimates with respect to the time variable t , we obtain uniform sharp two-sided estimates for the Green functions of $\{\Delta + a^\alpha \Delta^{\alpha/2}; a \in (0, 1]\}$ in half-space-like $C^{1,1}$ domains in \mathbb{R}^d .

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1 Introduction and Setup

This paper is a natural continuation of [5] where small time sharp two-sided estimates for the Dirichlet heat kernel of $\Delta + \Delta^{\alpha/2}$ on any $C^{1,1}$ open sets and large time sharp two-sided estimates for bounded $C^{1,1}$ open sets are obtained. In this paper we give sharp two-sided estimates for the Dirichlet heat kernel of $\Delta + \Delta^{\alpha/2}$ on half-space-like $C^{1,1}$ domains for all time. The large time Dirichlet heat kernel estimates for half-space-like domains are very different from those for bounded open sets. See below for the definition of half-space-like $C^{1,1}$ open sets.

Throughout this paper, we assume that $d \geq 1$ is an integer and $\alpha \in (0, 2)$. Let $X^0 = (X_t^0, t \geq 0)$ be a Brownian motion in \mathbb{R}^d with generator $\Delta = \sum_{i=1}^d \frac{\partial^2}{\partial x_i^2}$, and $Y = (Y_t, t \geq 0)$ be an independent (rotationally) symmetric α -stable process in \mathbb{R}^d whose generator is the fractional Laplacian $\Delta^{\alpha/2}$.

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For $u \in C_c^\infty(\mathbb{R}^d)$, the space of smooth functions with compact support, the fractional Laplacian can be written in the form

$$\Delta^{\alpha/2}u(x) = \lim_{\varepsilon \downarrow 0} \int_{\{y \in \mathbb{R}^d: |y-x| > \varepsilon\}} (u(y) - u(x)) \frac{\mathcal{A}(d, \alpha)}{|x-y|^{d+\alpha}} dy, \quad (1.1)$$

where $\mathcal{A}(d, \alpha) := \alpha 2^{\alpha-1} \pi^{-d/2} \Gamma(\frac{d+\alpha}{2}) \Gamma(1 - \frac{\alpha}{2})^{-1}$. Here Γ is the Gamma function defined by $\Gamma(\lambda) := \int_0^\infty t^{\lambda-1} e^{-t} dt$ for every $\lambda > 0$.

For any $a > 0$, we define X^a by $X_t^a := X_t^0 + aY_t$. We will call the process X^a the independent sum of the Brownian motion X^0 and the symmetric α -stable process Y with weight $a > 0$. The Lévy process X^a is uniquely determined by its characteristic function

$$\mathbb{E}_x \left[e^{i\xi \cdot (X_t^a - X_0^a)} \right] = e^{-t(|\xi|^2 + a^\alpha |\xi|^\alpha)} \quad \text{for every } x \in \mathbb{R}^d \text{ and } \xi \in \mathbb{R}^d$$

and its infinitesimal generator is $\Delta + a^\alpha \Delta^{\alpha/2}$. Since

$$a^\alpha |\xi|^\alpha = \int_{\mathbb{R}^d} (1 - \cos(\xi \cdot y)) \frac{a^\alpha \mathcal{A}(d, \alpha)}{|y|^{d+\alpha}} dy,$$

X^a has Lévy intensity function

$$J^a(x, y) = j^a(|x - y|) := a^\alpha \mathcal{A}(d, \alpha) |x - y|^{-(d+\alpha)}.$$

The function $J^a(x, y)$ determines a Lévy system for X^a , which describes the jumps of the process X^a : for any non-negative measurable function f on $\mathbb{R}_+ \times \mathbb{R}^d \times \mathbb{R}^d$ with $f(s, y, y) = 0$ for all $y \in \mathbb{R}^d$, any stopping time T (with respect to the filtration of X^a) and any $x \in \mathbb{R}^d$,

$$\mathbb{E}_x \left[\sum_{s \leq T} f(s, X_{s-}^a, X_s^a) \right] = \mathbb{E}_x \left[\int_0^T \left(\int_{\mathbb{R}^d} f(s, X_s^a, y) J^a(X_s^a, y) dy \right) ds \right] \quad (1.2)$$

(see, for example, [8, Proof of Lemma 4.7] and [9, Appendix A]).

Let $p^a(t, x, y)$ be the transition density of X^a with respect to the Lebesgue measure on \mathbb{R}^d . The function $p^a(t, x, y)$ is smooth on $(0, \infty) \times \mathbb{R}^d \times \mathbb{R}^d$. For any $\lambda > 0$, $(\lambda X_{\lambda^{-2}t}^a, t \geq 0)$ has the same distribution as $(X_t^{a\lambda^{(\alpha-2)/\alpha}}, t \geq 0)$ (see the second paragraph of [5, Section 2]), so we have

$$p^{a\lambda^{(\alpha-2)/\alpha}}(t, x, y) = \lambda^{-d} p^a(\lambda^{-2}t, \lambda^{-1}x, \lambda^{-1}y) \quad \text{for } t > 0 \text{ and } x, y \in \mathbb{R}^d. \quad (1.3)$$

For $a > 0$ and $C > 0$, define

$$h_C^a(t, x, y) := \left(t^{-d/2} \wedge (a^\alpha t)^{-d/\alpha} \right) \wedge \left(t^{-d/2} e^{-C|x-y|^2/t} + \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) \right). \quad (1.4)$$

Here and in the sequel, we use “:=” as a way of definition and, for $a, b \in \mathbb{R}$, $a \wedge b := \min\{a, b\}$ and $a \vee b := \max\{a, b\}$. The following sharp two-sided estimates on $p^a(t, x, y)$ follow from (1.3) and the main results in [10, 22] that give the sharp estimates on $p^1(t, x, y)$.

Theorem 1.1 *There are constants $c, C_1 \geq 1$ such that, for all $a \in [0, \infty)$ and $(t, x, y) \in (0, \infty] \times \mathbb{R}^d \times \mathbb{R}^d$*

$$c^{-1} h_{C_1}^a(t, x, y) \leq p^a(t, x, y) \leq c h_{1/C_1}^a(t, x, y).$$

We record a simple but useful observation. Its proof will be given at the end of this section.

Proposition 1.2 *For every $c > 0$ and $c_1 > 0$, there is a constant $c_2 \geq 1$ such that for any $a > 0$,*

$$c_2^{-1} \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) \leq h_c^a(t, x, y) \leq c_2 \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right)$$

holds when either $t \geq c_1 a^{-2\alpha/(2-\alpha)}$ or $|x-y| \geq a^{-\alpha/(2-\alpha)}$.

Recall that a domain (an connected open set) D in \mathbb{R}^d (when $d \geq 2$) is said to be $C^{1,1}$ if there exist a localization radius $R_0 > 0$ and a constant $\Lambda_0 > 0$ such that for every $z \in \partial D$, there exist a $C^{1,1}$ function $\psi = \psi_z : \mathbb{R}^{d-1} \rightarrow \mathbb{R}$ satisfying $\psi(0) = 0$, $\nabla \psi(0) = (0, \dots, 0)$, $\|\nabla \psi\|_\infty \leq \Lambda_0$, $|\nabla \psi(x) - \nabla \psi(z)| \leq \Lambda_0 |x - z|$, and an orthonormal coordinate system CS_z : $y = (y_1, \dots, y_{d-1}, y_d) := (\tilde{y}, y_d)$ with origin at z such that $B(z, R_0) \cap D = \{y = (\tilde{y}, y_d) \in B(0, R_0) \text{ in } CS_z : y_d > \psi(\tilde{y})\}$. The pair (R_0, Λ_0) will be called the $C^{1,1}$ characteristics of the domain D .

For an open set $D \subset \mathbb{R}^d$ and $x \in D$, we will use $\delta_D(x)$ to denote the Euclidean distance between x and D^c . For a domain $D \subset \mathbb{R}^d$ and $\lambda_0 \geq 1$, we say *the path distance in D is comparable to the Euclidean distance with characteristic λ_0* if for every $x, y \in D$, there is a rectifiable curve l in D connecting x to y so that the length of l is no larger than $\lambda_0 |x - y|$. Clearly, such a property holds for all bounded $C^{1,1}$ domains, $C^{1,1}$ domains with compact complements and domains above the graphs of bounded $C^{1,1}$ functions.

For any open subset $D \subset \mathbb{R}^d$, we use τ_D^a to denote the first time the process X^a exits D . We define the process $X^{a,D}$ by $X_t^{a,D} = X_t^a$ for $t < \tau_D^a$ and $X_t^{a,D} = \partial$ for $t \geq \tau_D^a$, where ∂ is a cemetery point. $X^{a,D}$ is called the subprocess of X^a in D . The generator of $X^{a,D}$ is $(\Delta + a^\alpha \Delta^{\alpha/2})|_D$. It follows from [10] that $X^{a,D}$ has a continuous transition density $p_D^a(t, x, y)$ with respect to the Lebesgue measure.

One can easily see that, when D is bounded, the operator $-(\Delta + a^\alpha \Delta^{\alpha/2})|_D$ has discrete spectrum. In this case, we use $\lambda_1^{a,D} > 0$ to denote the smallest eigenvalue of $-(\Delta + a^\alpha \Delta^{\alpha/2})|_D$.

The following is a particular case of a more general result proved in [5, Theorem 1.3] (cf. Proposition 1.2 above).

Theorem 1.3 *Suppose that D is a $C^{1,1}$ domain in \mathbb{R}^d with characteristics (R_0, Λ_0) such that the path distance in D is comparable to the Euclidean distance with characteristic λ_0 .*

- (i) *For every $M > 0$ and $T > 0$, there are constants $c_1 = c_1(R_0, \Lambda_0, \lambda_0, M, \alpha, T) \geq 1$ and $C_2 = C_2(R_0, \Lambda_0, \lambda_0, M, \alpha, T) \geq 1$ such that for all $a \in (0, M]$ and $(t, x, y) \in (0, T] \times D \times D$,*

$$\begin{aligned} c_1^{-1} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) h_{C_2}^a(t, x, y) \\ \leq p_D^a(t, x, y) \leq c_1 \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) h_{1/C_2}^a(t, x, y). \end{aligned}$$

- (ii) *Suppose in addition that D is bounded. For every $M > 0$ and $T > 0$, there is a constant $c_2 = c_2(D, M, \alpha, T) \geq 1$ so that for all $a \in (0, M]$ and $(t, x, y) \in [T, \infty) \times D \times D$,*

$$c_2^{-1} e^{-t \lambda_1^{a,D}} \delta_D(x) \delta_D(y) \leq p_D^a(t, x, y) \leq c_2 e^{-t \lambda_1^{a,D}} \delta_D(x) \delta_D(y).$$

Note that Theorem 1.3 does not give large time estimates for $p_D^a(t, x, y)$ when D is unbounded. The goal of this paper is to establish two-sided large time estimates on $p_D^a(t, x, y)$ for a large class of unbounded $C^{1,1}$ domains, namely half-space-like $C^{1,1}$ domains. A domain D is said to be half-space-like if, after isometry, there exist two real numbers $b_1 \leq b_2$ such that $\mathbb{H}_{b_2} \subset D \subset \mathbb{H}_{b_1}$. Here and throughout this paper, \mathbb{H}_b stands for the set $\{x = (x_1, \dots, x_d) \in \mathbb{R}^d : x_d > b\}$. We will denote \mathbb{H}_0 by \mathbb{H} .

Now we are in a position to state the main result of this paper. For $a > 0$, define $\phi_a(r) := r \wedge (r/a)^{\alpha/2}$.

Theorem 1.4 *Suppose D is a half-space-like $C^{1,1}$ domain with $C^{1,1}$ characteristic (R_0, Λ_0) and $\mathbb{H}_b \subset D \subset \mathbb{H}$ for some $b > 0$ such that the path distance in D is comparable to the Euclidean distance with characteristic λ_0 . Then for any $M \geq 1$, there exist constants $c_i = c_i(R_0, \Lambda_0, \lambda_0, M, \alpha, b) \geq 1$, $i = 1, 2$, such that for all $a \in (0, M]$ and $(t, x, y) \in (0, \infty) \times D \times D$,*

$$\begin{aligned} & c_1^{-1} \left(1 \wedge \frac{\phi_a(\delta_D(x))}{\sqrt{t}} \right) \left(1 \wedge \frac{\phi_a(\delta_D(y))}{\sqrt{t}} \right) h_{c_2}^a(t, x, y) \\ & \leq p_D^a(t, x, y) \leq c_1 \left(1 \wedge \frac{\phi_a(\delta_D(x))}{\sqrt{t}} \right) \left(1 \wedge \frac{\phi_a(\delta_D(y))}{\sqrt{t}} \right) h_{1/c_2}^a(t, x, y). \end{aligned} \quad (1.5)$$

Remark 1.5 (i) The Lévy exponent for X^a is $\Phi_a(|\xi|)$ with $\Phi_a(r) := r^2 + a^\alpha r^\alpha$. The function $\phi_a(r)$ is related to $\Phi_a(r)$ as follows.

$$\frac{1}{\Phi_a(1/r)} = \frac{1}{r^{-2} + a^\alpha r^{-\alpha}} \asymp \frac{1}{r^{-2}} \wedge \frac{1}{(a/r)^\alpha} = r^2 \wedge (r/a)^\alpha = \phi_a(r)^2.$$

Here for two non-negative functions f and g , the notation $f \asymp g$ means that there is a positive constant $c \geq 1$ so that $g(x)/c \leq f(x) \leq cg(x)$ in the common domain of definition for f and g . Hence in view of Theorem 1.1, the estimate (1.5) can be restated as follows. For every $M > 0$, there are constants $c_1, c_2 \geq 1$ so that for every $a \in (0, M]$ and $(t, x, y) \in (0, \infty) \times D \times D$,

$$\begin{aligned} & c_1^{-1} \left(1 \wedge \frac{1}{t\Phi_a(1/\delta_D(x))} \right)^{1/2} \left(1 \wedge \frac{1}{t\Phi_a(1/\delta_D(y))} \right)^{1/2} p^a(t, c_2x, c_2y) \\ & \leq p_D^a(t, x, y) \leq c_1 \left(1 \wedge \frac{1}{t\Phi_a(1/\delta_D(x))} \right)^{1/2} \left(1 \wedge \frac{1}{t\Phi_a(1/\delta_D(y))} \right)^{1/2} p^a(t, x/c_2, y/c_2). \end{aligned} \quad (1.6)$$

We conjecture that the above Dirichlet heat kernel estimates hold for a large class of rotationally symmetric Lévy processes in \mathbb{R}^d ; see [6, Conjecture].

(ii) Note that $t \leq a^{2\alpha/(\alpha-2)}$ if and only if $(a^\alpha t)^{-d/\alpha} \geq t^{-d/2}$. If $(\delta_D(x)/a)^{\alpha/2} < \delta_D(x)$, then $\delta_D(x) \geq a^{\alpha/(\alpha-2)}$ and so $\delta_D(x) \wedge (\delta_D(x)/a)^{\alpha/2} \geq a^{\alpha/(\alpha-2)}$. Thus when $t \leq a^{2\alpha/(\alpha-2)}$ and $(\delta_D(x)/a)^{\alpha/2} < \delta_D(x)$, we have $\frac{(\delta_D(x)/a)^{\alpha/2}}{\sqrt{t}} \geq \frac{a^{\alpha/(\alpha-2)}}{a^{\alpha/(\alpha-2)}} = 1$, and consequently

$$1 \wedge \frac{\delta_D(x) \wedge (\delta_D(x)/a)^{\alpha/2}}{\sqrt{t}} = 1 = 1 \wedge \frac{\delta_D(x)}{\sqrt{t}}.$$

Hence in view of Theorem 1.1 and Proposition 1.2, the statement of Theorem 1.4 can be restated as follows. For all $a \in (0, M]$ and $(t, x, y) \in (0, a^{2\alpha/(\alpha-2)}) \times D \times D$,

$$c_1^{-1} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-c_2|x-y|^2/t} + t^{-d/2} \wedge \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) \right)$$

$$\leq p_D^a(t, x, y) \leq c_1 \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-|x-y|^2/(c_2 t)} + t^{-d/2} \wedge \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) \right) \quad (1.7)$$

and for all $a \in (0, M]$ and $(t, x, y) \in [a^{2\alpha/(\alpha-2)}, \infty) \times D \times D$,

$$\begin{aligned} & c_1^{-1} \left(1 \wedge \frac{\delta_D(x) \wedge (a^{-1} \delta_D(x))^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y) \wedge (a^{-1} \delta_D(y))^{\alpha/2}}{\sqrt{t}} \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) \\ & \leq p_D^a(t, x, y) \leq \\ & c_1 \left(1 \wedge \frac{\delta_D(x) \wedge (a^{-1} \delta_D(x))^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y) \wedge (a^{-1} \delta_D(y))^{\alpha/2}}{\sqrt{t}} \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right). \quad (1.8) \end{aligned}$$

In fact, Theorem 1.4 will be proved in this form. \square

Remark 1.6 Unlike [6, 11], there are dramatic differences between the behavior of the heat kernel $p_D^a(x, y)$ on half-space-like $C^{1,1}$ domains and disconnected half-space-like $C^{1,1}$ open sets even if x and y are in the same connected component. For example, if D is $\mathbb{H} \cup B(x_0, 1)$ where $x_0 = (0, \dots, 0, -2)$ and $x, y \in B(x_0, 1)$, then, as $a \rightarrow 0$, $p_D^a(x, y)$ converges to $p_{B(x_0, 1)}^0(x, y)$, the Dirichlet heat kernel for Brownian motion on $B(x_0, 1)$. Thus, in this case, the heat kernel estimates for $p_D^a(t, x, y)$ when t is large cannot be of the form (1.5) even if x and y are in the same connected component. Furthermore, as one can see from [5, Theorem 1.3], when D is a disconnected half-space-like $C^{1,1}$ open set (containing bounded connected component), we can not expect that the heat kernel estimates for $p_D^a(x, y)$ to be written in a simple form as the one in (1.5). To keep our exposition as transparent as possible, we are content with establishing the heat kernel estimates for half-space-like $C^{1,1}$ domains. \square

Integrating the heat kernel estimates in Theorem 1.4 with respect to t , we get sharp two-sided estimates on the Green function $G_D^a(x, y) := \int_0^\infty p_D^a(t, x, y) dt$ for X^a in half-space-like $C^{1,1}$ domains D .

Define for $d \geq 1$ and $a > 0$,

$$f_D^a(x, y) = \begin{cases} \frac{1}{|x-y|^{d-\alpha}} \left(a^{-\alpha/2} \wedge \frac{\phi_a(\delta_D(x))}{|x-y|^{\alpha/2}} \right) \left(a^{-\alpha/2} \wedge \frac{\phi_a(\delta_D(y))}{|x-y|^{\alpha/2}} \right) & \text{when } d > \alpha, \\ \log \left(\left(1 + a \frac{\phi_a(\delta_D(x)) \phi_a(\delta_D(y))}{|x-y|} \right)^{1/a} \right) & \text{when } d = 1 = \alpha, \\ \frac{\phi_a(\delta_D(x)) \phi_a(\delta_D(y))}{|x-y|} \wedge \left(a^{-1} (\phi_a(\delta_D(x)) \phi_a(\delta_D(y)))^{(\alpha-1)/\alpha} \right) & \text{when } d = 1 < \alpha. \end{cases} \quad (1.9)$$

For $d \geq 2$ and $a > 0$, define

$$g_D^a(x, y) = \begin{cases} \frac{1}{|x-y|^{d-2}} \left(1 \wedge \frac{\delta_D(x) \delta_D(y)}{|x-y|^2} \right) & \text{when } d \geq 3, \\ \log \left(1 + \frac{a^{2\alpha/(\alpha-2)} \wedge (\delta_D(x) \delta_D(y))}{|x-y|^2} \right) & \text{when } d = 2, \end{cases}$$

for $d = 1$ and $a > 0$, define

$$g_D^a(x, y) = \begin{cases} (\delta_D(x)\delta_D(y))^{1/2} \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|} \wedge (a^{-\alpha}(\delta_D(x)\delta_D(y))^{(\alpha-1)/2}) & \text{when } \alpha \in (1, 2), \\ \frac{\delta_D(x)\delta_D(y)}{|x-y|} \wedge \log \left(1 + a(\delta_D(x)\delta_D(y))^{1/2} \right)^{1/a} & \text{when } \alpha = 1, \\ (\delta_D(x)\delta_D(y))^{1/2} \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|} \wedge a^{\alpha/(\alpha-2)} & \text{when } \alpha \in (0, 1). \end{cases}$$

Theorem 1.7 Suppose D is a half-space-like $C^{1,1}$ domain with $C^{1,1}$ characteristic (R_0, Λ_0) and $\mathbb{H}_b \subset D \subset \mathbb{H}$ for some $b > 0$ such that the path distance in D is comparable to the Euclidean distance with characteristic λ_0 . Then for any $M > 0$, there exists a constant $c = c(M, R_0, \Lambda_0, \lambda_0, b, \alpha) \geq 1$ such that for all $a \in (0, M]$ and $(x, y) \in D \times D$,

$$c^{-1}g_D^a(x, y) \leq G_D^a(x, y) \leq cg_D^a(x, y) \quad \text{when } |x - y| \leq a^{-\alpha/(2-\alpha)}, \quad (1.10)$$

$$c^{-1}f_D^a(x, y) \leq G_D^a(x, y) \leq cf_D^a(x, y) \quad \text{when } |x - y| \geq a^{-\alpha/(2-\alpha)}. \quad (1.11)$$

Remark 1.8 (i) Note that, when $d \geq 3$, $g_D^a(x, y)$ is independent of a and is comparable to the Green function of Brownian motion in a bounded $C^{1,1}$ domain or in a domain above the graph of a bounded $C^{1,1}$ function. On the other hand, when $d \leq 2$, $g_D^a(x, y)$ depends on a , which is due to recurrent nature of one- and two-dimensional Brownian motion.

(ii) Observe that if $(X_t^{a,D}, t \geq 0)$ is the subprocess in D of the independent sum of a Brownian motion and a symmetric α -stable process in \mathbb{R}^d with weight a , then $(\lambda X_{\lambda^{-2}t}^{a,D}, t \geq 0)$ is the subprocess in λD of the independent sum of a Brownian motion and a symmetric α -stable process in \mathbb{R}^d with weight $a\lambda^{(\alpha-2)/\alpha}$ (see the second paragraph of [5, Section 2]). Consequently for any $\lambda > 0$, we have

$$p_{\lambda D}^{a\lambda^{(\alpha-2)/\alpha}}(t, x, y) = \lambda^{-d} p_D^a(\lambda^{-2}t, \lambda^{-1}x, \lambda^{-1}y) \quad \text{for } t > 0 \text{ and } x, y \in \lambda D. \quad (1.12)$$

When D is a half space, we see from (1.12) that Theorems 1.4 and 1.7 hold with $M = \infty$.

(iii) The estimates in Theorems 1.4 and 1.7 are uniform in $a \in (0, M]$ in the sense that the constants c_1 , c_2 and c in the estimates are independent of $a \in (0, M]$. Since X^a converges weakly to X^0 , by taking $a \rightarrow 0$ these estimates yield the following estimates for the heat kernel $p_D^0(t, x, y)$ and Green function $G^0(x, y)$ of Brownian motion in half-space-like domains D in which the path distance is comparable to the Euclidean distance:

$$\begin{aligned} c_1^{-1} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) t^{-d/2} e^{-c_2|x-y|^2/t} \\ \leq p_D^0(t, x, y) \leq c_1 \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) t^{-d/2} e^{-|x-y|^2/(c_2 t)} \end{aligned} \quad (1.13)$$

for every $(t, x, y) \in (0, \infty) \times D \times D$, and

$$c_2^{-1} g_D^0(x, y) \leq G_D^0(x, y) \leq c_2 g_D^0(x, y) \quad \text{for } x, y \in D. \quad (1.14)$$

The estimates (1.13) and (1.14) extend the main results in [20], where the corresponding estimates were established for domains in \mathbb{R}^d with $d \geq 3$ that are above the graphs of bounded $C^{1,1}$ functions.

(iv) By Theorem 1.4, the boundary decay rate of the Dirichlet heat kernel of $\Delta + \Delta^{\alpha/2}$ is given by $1 \wedge \frac{\delta_D(x) \wedge \delta_D(y)}{\sqrt{t}}^{\alpha/2}$. This indicates that the Dirichlet heat kernel estimates for $\Delta + \Delta^{\alpha/2}$ in half-space-like $C^{1,1}$ domains cannot be obtained by a “simple” perturbation argument from Δ nor from $\Delta^{\alpha/2}$.

The main difficulty of this paper is to obtain the correct boundary decay rate of the Dirichlet heat kernel of $\Delta + \Delta^{\alpha/2}$. In [5], the correct boundary decay rate for small t was established by using some exit distribution estimates obtained in [7]. Unfortunately the estimates in [7] are not suitable for the present case. Thus, in this paper we give some different forms of exit distribution estimates that are suitable for large time estimates. The first step is, similar to [2, 12, 7], to compute $(\Delta + \Delta^{\alpha/2})h$ for certain test functions. But unlike [7], we do not use combinations of test functions to serve as subharmonic and superharmonic functions to obtain our desired estimates. Instead, we use a generalization of Dynkin's formula to obtain the desired exit distribution estimates directly. We believe that our approach to obtain the correct boundary decay rate is quite general and may be used for other types of jump processes.

Throughout this paper, the constants $C_1, C_2, C_3, R_0, R_1, R_2, R_3$ will be fixed. The lower case constants c_1, c_2, \dots will denote generic constants whose exact values are not important and can change from one appearance to another. The dependence of the lower case constants on the dimension d will not be mentioned explicitly. We will use ∂ to denote a cemetery point and for every function f , we extend its definition to ∂ by setting $f(\partial) = 0$. We will use dx or $m(dx)$ to denote the Lebesgue measure in \mathbb{R}^d . For a Borel set $A \subset \mathbb{R}^d$, we also use $|A|$ to denote its d -dimensional Lebesgue measure. For every function f , let $f^+ := f \vee 0$.

In the remainder of this paper we will always assume that D is a half-space-like $C^{1,1}$ domain with $C^{1,1}$ characteristic (R_0, Λ_0) and $\mathbb{H}_b \subset D \subset \mathbb{H}$ for some $b > 0$ such that the path distance in D is comparable to the Euclidean distance with characteristic λ_0 and that t_0, x_0 and y_0 are described as below.

Fix $t_0 \geq b^2$ and let e_d be the unit vector in the direction of the x_d -axis. For x and y in D , define the points

$$x_0 := x + 2t_0^{1/2}e_d \quad \text{and} \quad y_0 := y + 2t_0^{1/2}e_d. \quad (1.15)$$

Observe that

$$\delta_D(x_0) \geq \delta_{\mathbb{H}}(x_0) > t_0^{1/2}, \quad \delta_D(y_0) \geq \delta_{\mathbb{H}}(y_0) > t_0^{1/2}, \quad (1.16)$$

and $|x - x_0| = |y - y_0| = 2t_0^{1/2}$. Note that when $D = \mathbb{H}$, we can take t_0 to be any positive number. Now as a consequence of Theorem 1.3, we have the following result.

Lemma 1.9 *There exists $c = c(b, t_0, R_0, \Lambda_0, \alpha, \lambda_0) \geq 1$ such that for all $x, z \in D$,*

$$c^{-1} (1 \wedge \delta_D(x)) \leq \frac{p_D^1(t_0, x, z)}{p_D^1(t_0, x_0, z)} \leq c (1 \wedge \delta_D(x)). \quad (1.17)$$

Proof. Let C_2 be the constant in Theorem 1.3 (i) with $T = t_0$. From Proposition 1.2 and Theorem 1.3 (i), it is easy to see that

$$h_{C_2}^1(t_0, x, y) \asymp 1 \wedge \frac{1}{|x - y|^{d+\alpha}} \quad \text{and} \quad h_{1/C_2}^1(t_0, x, y) \asymp 1 \wedge \frac{1}{|x - y|^{d+\alpha}}. \quad (1.18)$$

By Theorem 1.3 (i) and (1.16), we see that

$$c_1^{-1} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t_0}} \right) \left(\frac{h_{C_2}^1(t_0, x, z)}{h_{1/C_2}^1(t_0, x_0, z)} \right) \leq \frac{p_D^1(t_0, x, z)}{p_D^1(t_0, x_0, z)} \leq c_1 \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t_0}} \right) \left(\frac{h_{1/C_2}^1(t_0, x, z)}{h_{C_2}^1(t_0, x_0, z)} \right). \quad (1.19)$$

For $z \in B(x_0, 2^{-1}t_0^{1/2})$ we have

$$\frac{3}{2}t_0^{1/2} \leq |x_0 - x| - |z - x_0| \leq |x - z| \leq |z - x_0| + |x_0 - x| = |z - x_0| + 2t_0^{1/2} \leq \frac{5}{2}t_0^{1/2}.$$

Similarly, for $z \in B(x, 2^{-1}t_0^{1/2})$ we have $\frac{3}{2}t_0^{1/2} \leq |x - z_0| \leq \frac{5}{2}t_0^{1/2}$. Thus in these cases, (1.17) follows from (1.19).

In the case $z \notin B(x, 2^{-1}t_0^{1/2}) \cup B(x_0, 2^{-1}t_0^{1/2})$, we have $|x - z| \leq |z - x_0| + |x_0 - x| = |z - x_0| + 2t_0^{1/2} \leq 5|z - x_0|$ and $|x_0 - z| \leq |z - x| + |x_0 - x| = |z - x| + 2t_0^{1/2} \leq 5|z - x|$. So $5^{-1}|x_0 - z| \leq |z - x| \leq 5|x_0 - z|$. Therefore by (1.18)

$$\frac{h_{1/C_2}^1(t_0, x, z)}{h_{C_2}^1(t_0, x_0, z)} \leq c_2 \quad \text{and} \quad \frac{h_{C_2}^1(t_0, x, z)}{h_{1/C_2}^1(t_0, x_0, z)} \geq c_3.$$

□

Lemma 1.10 *For any $M > 0$, there exists $c = c(b, t_0, R_0, \Lambda_0, \alpha, \lambda_0) \geq 1$ such that for all $a \in (0, M]$ and $x, z \in D$,*

$$\begin{aligned} c^{-1} (1 \wedge \delta_D(x)) (1 \wedge \delta_D(z)) h_{25C_2}^a(t_0, x_0, z) \\ \leq p_D^a(t_0, x, z) \leq c (1 \wedge \delta_D(x)) (1 \wedge \delta_D(z)) h_{1/(25C_2)}^a(t_0, x_0, z) \end{aligned} \quad (1.20)$$

where C_2 is the constant in Theorem 1.3 (i) with $T = t_0$.

Proof. By Theorem 1.3 (i), we see that

$$c_1^{-1} (1 \wedge \delta_D(x)) (1 \wedge \delta_D(z)) h_{C_2}^a(t_0, x, z) \leq p_D^a(t_0, x, z) \leq c_1 (1 \wedge \delta_D(x)) (1 \wedge \delta_D(z)) h_{1/(C_2)}^a(t_0, x, z). \quad (1.21)$$

By the same argument as in the proof of Lemma 1.9, $\frac{3}{2}t_0^{1/2} \leq |x - z| \leq \frac{5}{2}t_0^{1/2}$ for $z \in B(x_0, 2^{-1}t_0^{1/2})$, $\frac{3}{2}t_0^{1/2} \leq |x - z_0| \leq \frac{5}{2}t_0^{1/2}$ for $z \in B(x, 2^{-1}t_0^{1/2})$, and $5^{-1}|x_0 - z| \leq |z - x| \leq 5|x_0 - z|$ for $z \notin B(x, 2^{-1}t_0^{1/2}) \cup B(x_0, 2^{-1}t_0^{1/2})$. The assertion of the lemma follows by considering each cases in (1.21). □

The following elementary result will play an important role later in this paper. Recall that D , t_0 , x_0 and y_0 are described as above.

Lemma 1.11 *For any $t_0 \geq b^2$ and $M > 0$, there exists a constant $c = c(\alpha, M, t_0, b) > 1$ such that for any $a \in (0, M]$ and $(t, x) \in [t_0, \infty) \times D$,*

$$\begin{aligned} (1 \wedge \delta_D(x)) \left(1 \wedge \frac{\delta_{\mathbb{H}}(x_0) \wedge (a^{-1}\delta_{\mathbb{H}}(x_0))^{\alpha/2}}{\sqrt{t}} \right) &\leq c \left(1 \wedge \frac{\delta_D(x) \wedge (a^{-1}\delta_D(x))^{\alpha/2}}{\sqrt{t}} \right), \\ (1 \wedge \delta_D(x)) \left(1 \wedge \frac{\delta_{\mathbb{H}_b}(x_0) \wedge (a^{-1}\delta_{\mathbb{H}_b}(x_0))^{\alpha/2}}{\sqrt{t}} \right) &\geq c^{-1} \left(1 \wedge \frac{\delta_D(x) \wedge (a^{-1}\delta_D(x))^{\alpha/2}}{\sqrt{t}} \right). \end{aligned}$$

Proof. Note that

$$\delta_D(x) + t_0^{1/2} \leq \delta_{\mathbb{H}_b}(x_0) \leq \delta_D(x) + 2t_0^{1/2} \quad \text{and} \quad \delta_D(x) + 2t_0^{1/2} \leq \delta_{\mathbb{H}}(x_0) \leq \delta_D(x) + 3t_0^{1/2}.$$

When $\delta_D(x) > t_0^{1/2}$, we have $\delta_D(x) \leq \delta_{\mathbb{H}_b}(x_0) < \delta_{\mathbb{H}}(x_0) \leq 4\delta_D(x)$. Thus in this case, the conclusion of the lemma is trivial. From now on, we assume that $\delta_D(x) \leq t_0^{1/2}$. In this case, using the fact $t \geq t_0$ and $a \in (0, M]$, we have

$$\begin{aligned} (1 \wedge \delta_D(x)) \left(1 \wedge \frac{\delta_{\mathbb{H}}(x_0) \wedge (a^{-1}\delta_{\mathbb{H}}(x_0))^{\alpha/2}}{\sqrt{t}} \right) &\asymp (1 \wedge \delta_D(x)) \left(1 \wedge \frac{\delta_{\mathbb{H}_b}(x_0) \wedge (a^{-1}\delta_{\mathbb{H}_b}(x_0))^{\alpha/2}}{\sqrt{t}} \right) \\ &\asymp \delta_D(x) \left(1 \wedge \frac{1}{\sqrt{t}} \right) \asymp 1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \asymp 1 \wedge \frac{\delta_D(x) \wedge (a^{-1}\delta_D(x))^{\alpha/2}}{\sqrt{t}}. \end{aligned}$$

The proof is now complete. \square

Proof of Proposition 1.2. We first deal with the case $a = 1$. For $t \geq c_1$ and $r \geq 0$,

$$t^{-d/2}e^{-cr^2/t} \leq t^{-d/2} \frac{c_2}{(cr^2/t)^{(d+\alpha)/2}} \leq c_3 \frac{t^{\alpha/2}}{r^{d+\alpha}} \leq c_4 \frac{t}{r^{d+\alpha}}.$$

Hence for $t \geq c_1$,

$$t^{-d/\alpha} \wedge \left(t^{-d/2}e^{-cr^2/t} + t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right) \asymp t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}}.$$

Thus $h_c^1(t, x, y) \asymp t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}}$ on $[c_1, \infty) \times \mathbb{R}^d \times \mathbb{R}^d$. On the other hand, for $r \geq 1$,

$$t^{-d/2}e^{-cr^2/t} \leq t^{-d/2} \frac{c_5}{(cr^2/t)^{(d/2)+1}} = \frac{c_6 t}{r^{d+2}} \leq \frac{c_6 t}{r^{d+\alpha}}.$$

So for $t \in (0, c_1]$ and $r \geq 1$,

$$t^{-d/2}e^{-cr^2/t} + \left(t^{-d/2} \wedge \frac{t}{r^{d+\alpha}} \right) \asymp t^{-d/2} \wedge \frac{t}{r^{d+\alpha}} \asymp \frac{t}{r^{d+\alpha}} \asymp t^{-d/\alpha} \wedge \frac{t}{r^{d+\alpha}}.$$

Thus we conclude that $h_c^1(t, x, y) \asymp t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}}$ for $t \leq c_1$ and $|x-y| \geq 1$. In summary, we have

$$h_c^1(t, x, y) \asymp t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \tag{1.22}$$

when $t \geq c_1$ or $|x-y| \geq 1$. For $a > 0$, with $\lambda = a^{\alpha/(2-\alpha)}$, by (1.22)

$$\begin{aligned} h_c^a(t, x, y) &= \lambda^d h_c^1(\lambda^2 t, \lambda x, \lambda y) \\ &\asymp \lambda^d \left((\lambda^2 t)^{-d/\alpha} \wedge \frac{\lambda^2 t}{\lambda^{d+\alpha} |x-y|^{d+\alpha}} \right) = (a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}}, \end{aligned}$$

provided either $\lambda^2 t \geq c_1$ or $\lambda |x-y| \geq 1$. This proves the proposition. \square

2 Preliminary estimates

We will focus on the case $D = \mathbb{H}$ in Sections 2–4. In this section we will prove some preliminary estimates that will be used to establish our heat kernel estimates in \mathbb{H} . We start with some one-dimensional results.

Let S be the sum of a unit drift and an $\alpha/2$ -stable subordinator and let W be an independent one-dimensional Brownian motion. Define a process Z by $Z_t = W_{S_t}$. The process Z is simply the process X^1 in the case of dimension 1 defined in the previous section. We will use the fact that S is a complete subordinator, that is, the Lévy measure of S has a completely monotone density (for more details see [17] or [21]). Let $\bar{Z}_t := \sup\{0 \vee Z_s : 0 \leq s \leq t\}$ and let L_t be a local time of $\bar{Z} - Z$ at 0. L is also called a local time of the process Z reflected at the supremum. Then the right continuous inverse L_t^{-1} of L is a subordinator and is called the ladder time process of Z . The process $\bar{Z}_{L_t^{-1}}$ is also a subordinator and is called the ladder height process of Z . (For the basic properties of the ladder time and ladder height processes, we refer our readers to [1, Chapter 6].) Let $V(dr)$ denote the potential measure of the ladder height process $\bar{Z}_{L_t^{-1}}$ of Z and $v(r)$ its density, which is a decreasing function on $[0, \infty)$. We know by [16, (5.1)] that

$$v(r) \asymp 1 \wedge r^{\alpha/2-1} \quad \text{for } r > 0. \quad (2.1)$$

Let $G_{(0,\infty)}$ be the Green function of $Z^{(0,\infty)}$, the subprocess of Z in $(0, \infty)$. By using [1, Theorem 20, p. 176] which was originally proved in [18], the following formula for $G_{(0,\infty)}$ was shown in [14, Proposition 2.8]:

$$G_{(0,\infty)}(x, y) = \int_0^{x \wedge y} v(z)v(z + |x - y|)dz. \quad (2.2)$$

For any $r > 0$, let $G_{(0,r)}$ be the Green function of $Z^{(0,r)}$, the subprocess of Z in $(0, r)$. Then we have the following result.

Proposition 2.1 *There exists $c = c(\alpha) > 0$ such that for every $r \in (0, \infty)$,*

$$\int_0^r G_{(0,r)}(x, y)dy \leq c(r \wedge r^{\alpha/2}) \left((x \wedge x^{\alpha/2}) \wedge ((r - x) \wedge (r - x)^{\alpha/2}) \right), \quad x \in (0, r).$$

Proof. For any $x \in (0, r)$, by (2.2), we have

$$\begin{aligned} \int_0^r G_{(0,r)}(x, y)dy &\leq \int_0^r G_{(0,\infty)}(x, y)dy \\ &= \int_0^x \int_{x-y}^x v(z)v(y+z-x)dzdy + \int_x^r \int_0^x v(z)v(y+z-x)dzdy \\ &= \int_0^x v(z) \int_{x-z}^x v(y+z-x)dydz + \int_0^x v(z) \int_x^r v(y+z-x)dydz \\ &\leq 2V((0, r))V((0, x)). \end{aligned}$$

Thus, by (2.1)

$$\int_0^r G_{(0,r)}(x, y)dy \leq c(r \wedge r^{\alpha/2})(x \wedge x^{\alpha/2}), \quad x \in (0, r).$$

Now the proposition follows by the symmetry. \square

Now we return to the process X^1 in \mathbb{R}^d . Recall that $C_c^\infty(\mathbb{R}^d)$ is contained in the domain of the L_2 -generator $\Delta + \Delta^{\alpha/2}$ of X^1 and

$$(\Delta + \Delta^{\alpha/2})\phi(x) = \Delta\phi(x) + \int_{\mathbb{R}^d} (\phi(x+y) - \phi(x) - (\nabla\phi(x) \cdot y)1_{B(0,\varepsilon)}(y))j^1(|y|)dy, \quad \forall \phi \in C_c^\infty(\mathbb{R}^d)$$

(see [19, Section 4.1]). Using the argument in [13, pp. 152], one can easily see that the last formula on [13, pp. 152] is valid for X^1 for all $d \geq 1$. Thus we have the following generalization of Dynkin's formula: for every ϕ in $C_c^\infty(\mathbb{R}^d)$ and $x \in U$,

$$\mathbb{E}_x \left[\phi \left(X_{\tau_U}^1 \right) \right] - \phi(x) = \int_U G_U^1(x, y) (\Delta + \Delta^{\alpha/2})\phi(y) dy = \mathbb{E}_x \int_0^{\tau_U^1} (\Delta + \Delta^{\alpha/2})\phi(X_s^1) ds. \quad (2.3)$$

The following estimates on harmonic measures will play a crucial role in Section 3.

Theorem 2.2 *For any $R > 0$, there exists a constant $c = c(\alpha, R) > 0$ such that for every $r \geq R$ and open set $U \subset B(0, r)$,*

$$\mathbb{P}_x \left(X_{\tau_U}^1 \in B(0, r)^c \right) \leq c r^{-\alpha} \int_U G_U^1(x, y) dy, \quad \text{for every } x \in U \cap B(0, r/2).$$

Proof. Without loss of generality, we assume that $R \in (0, 1)$. Take a sequence of radial functions ϕ_k in $C_c^\infty(\mathbb{R}^d)$ such that $0 \leq \phi_k \leq 1$,

$$\phi_k(y) = \begin{cases} 0, & \text{if } |y| < 1/2 \\ 1, & \text{if } 1 \leq |y| \leq k+1 \\ 0, & \text{if } |y| > k+2, \end{cases}$$

and that $\sum_{i,j} \left| \frac{\partial^2}{\partial y_i \partial y_j} \phi_k \right|$ is uniformly bounded. Define $\phi_{k,r}(y) = \phi_k(\frac{y}{r})$. Then we have $0 \leq \phi_{k,r} \leq 1$,

$$\phi_{k,r}(y) = \begin{cases} 0, & \text{if } |y| < r/2 \\ 1, & \text{if } r \leq |y| \leq r(k+1) \\ 0, & \text{if } |y| > r(k+2), \end{cases} \quad \text{and} \quad \sup_{y \in \mathbb{R}^d} \sum_{i,j} \left| \frac{\partial^2}{\partial y_i \partial y_j} \phi_{k,r}(y) \right| < c_1 r^{-2}.$$

Using this inequality, we have for $r \geq R$

$$\begin{aligned} \sup_{k \geq 1} \sup_{z \in \mathbb{R}^d} \left| (\Delta + \Delta^{\alpha/2})\phi_{k,r}(z) \right| &\leq \sup_{k \geq 1} \sup_{z \in \mathbb{R}^d} |\Delta\phi_{k,r}(z)| + \sup_{k \geq 1} \sup_{z \in \mathbb{R}^d} |\Delta^{\alpha/2}\phi_{k,r}(z)| \\ &\leq c_1 r^{-2} + \sup_{k \geq 1} \sup_{z \in \mathbb{R}^d} \left| \int_{\mathbb{R}^d} (\phi_{k,r}(z+y) - \phi_{k,r}(z) - (\nabla\phi_{k,r}(z) \cdot y)1_{B(0,r)}(y))j^1(|y|)dy \right| \\ &\leq c_1 r^{-2} + c_2 \sup_{k \geq 1} \sup_{z \in \mathbb{R}^d} \left(\int_{\{|y| \leq r\}} \left| \frac{\phi_{k,r}(z+y) - \phi_{k,r}(z) - (\nabla\phi_{k,r}(z) \cdot y)}{|y|^{d+\alpha}} \right| dy + \int_{\{r < |y|\}} |y|^{-d-\alpha} dy \right) \\ &\leq c_1 r^{-2} + c_3 \left(\frac{1}{r^2} \int_{\{|y| \leq r\}} \frac{|y|^2}{|y|^{d+\alpha}} dy + \int_{\{r < |y|\}} |y|^{-d-\alpha} dy \right) \leq c_1 r^{-2} + c_4 r^{-\alpha}. \end{aligned} \quad (2.4)$$

When $U \subset B(0, r)$ for some $r \geq R$, we get, by combining (2.3) and (2.4), that for any $x \in U \cap B(0, r/2)$,

$$\mathbb{P}_x \left(X_{\tau_U}^1 \in B(0, r)^c \right) \leq \lim_{k \rightarrow \infty} \mathbb{E}_x \left[\phi_{k,r} \left(X_{\tau_U}^1 \right) \right] \leq c_5 r^{-\alpha} \int_U G_U^1(x, y) dy.$$

□

In the remainder of this section we will establish a result (Lemma 2.4) that will be crucial for our heat kernel estimates in Section 4.

Let

$$\widehat{\Delta}^{\alpha/2}u(x) := \lim_{\varepsilon \downarrow 0} \int_{\{y \in \mathbb{R}^d : |y-x| > \varepsilon\}} (u(y) - u(x)) \frac{\mathcal{A}(d, \alpha)}{|x-y|^{d+\alpha}} dy. \quad (2.5)$$

Recall that $\widehat{\Delta}^{\alpha/2} = \Delta^{\alpha/2}$ on $C_c^\infty(\mathbb{R}^d)$. For $x \in \mathbb{R}^d$ and $p > 0$, set $w_p(x) := (x_d^+)^p$. For $0 < p < \alpha < 2$, let

$$\Lambda = \Lambda(\alpha, p) = \frac{p\mathcal{A}(d, -\alpha)}{\alpha} \int_0^1 \frac{t^{\alpha-p-1} - t^{p-1}}{(1-t)^\alpha} dt \int_{|y|=1, y_d \geq 0} y_d^\alpha m(dy), \quad (2.6)$$

with the convention that $m(dy)$ is the Dirac measure when $d = 1$. Then it follows from [12, Lemma 6.1] that

$$\widehat{\Delta}^{\alpha/2}w_p(x) = \Lambda(d, \alpha, p)w_{p-\alpha}(x), \quad x \in \mathbb{H}. \quad (2.7)$$

In particular, on \mathbb{H} we have

$$\widehat{\Delta}^{\alpha/2}w_p < 0, \quad 0 < p < \alpha/2; \quad \widehat{\Delta}^{\alpha/2}w_p = 0, \quad p = \alpha/2; \quad \widehat{\Delta}^{\alpha/2}w_p > 0, \quad \alpha/2 < p < \alpha. \quad (2.8)$$

Lemma 2.3 *Suppose $0 < p \leq \frac{\alpha}{2}$ and $R > 8$. Let $Q(a, b) := \{y \in \mathbb{H} : |\tilde{y}| < a, 0 < y_d < b\}$ and*

$$h_p(y) := w_p(y)\mathbf{1}_{Q(R, R)}(y), \quad y \in \mathbb{H}.$$

There exist constants $c_1, c_2 > 0$ such that for every $R > 8$ and $x \in Q(2R/3, 2R/3)$,

$$-c_1(x_d)^{p-\alpha} \leq \widehat{\Delta}^{\alpha/2}h_p(x) \leq -\Lambda(x_d)^{p-\alpha} \quad \text{when } 0 < p < \frac{\alpha}{2} \quad (2.9)$$

and

$$-c_1R^{-\alpha/2} \leq \widehat{\Delta}^{\alpha/2}h_{\alpha/2}(x) \leq -c_2R^{-\alpha/2} \quad \text{when } p = \frac{\alpha}{2}, \quad (2.10)$$

where $\Lambda = \Lambda(\alpha, p) > 0$ is the constant defined in (2.6).

Proof. Since $h_p(y) = w_p(y)$ for $y \in Q(R, R)$, by (2.8), we have for any $x \in Q(2R/3, 2R/3)$,

$$\begin{aligned} \widehat{\Delta}^{\alpha/2}h_p(x) &= \widehat{\Delta}^{\alpha/2}(h_p - w_p)(x) + \widehat{\Delta}^{\alpha/2}w_p(x) \\ &= - \int_{Q(R, R)^c} (y_d^+)^p \frac{\mathcal{A}(d, -\alpha)}{|x-y|^{d+\alpha}} dy + \widehat{\Delta}^{\alpha/2}w_p(x). \end{aligned}$$

Observe that for $x \in Q(2R/3, 2R/3)$ and $y \in Q(R, R)^c$, $|y-x| \geq |y|/3$. Thus for $x \in Q(2R/3, 2R/3)$, by the change of variable $z = R^{-1}y$,

$$\int_{Q(R, R)^c} \frac{(y_d^+)^p}{|x-y|^{d+\alpha}} dy \leq c_1 \int_{\{y \in \mathbb{R}^d : |y| > R\}} \frac{1}{|y|^{d+\alpha-p}} dy \leq c_2 R^{p-\alpha} \int_{\{z \in \mathbb{R}^d : |z| > 1\}} \frac{1}{|z|^{d+\alpha-p}} dz \leq c_3 R^{p-\alpha}.$$

The conclusion of the lemma now follows from the above two displays and (2.7) and (2.8). □

Lemma 2.4 *There exist $c = c(\alpha) > 0$ and $R_1 = R_1(\alpha) > 2$ such that for every $R > 8R_1$ and $x \in Q(R/4, R/2) \setminus Q(R/4, 2R_1)$, we have*

$$\mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R/2) \right) \geq c \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{R^{\alpha/2}},$$

where $V_R := Q(R/2, R/2) \setminus Q(R/2, R_1)$.

Proof. Put $p := (\alpha/4) \vee (\alpha - 1)$ and define

$$h_p(y) := w_p(y) \mathbf{1}_{Q(R, R)}(y) \quad \text{and} \quad h_{\alpha/2}(y) := w_{\alpha/2}(y) \mathbf{1}_{Q(R, R)}(y).$$

We choose $R_1 > 2$ large such that

$$\frac{\alpha}{2} \left(1 - \frac{\alpha}{2}\right) (R_1/2)^{\alpha-2} \leq |\Lambda|, \quad (2.11)$$

where Λ is the constant defined in (2.6). Obviously, with the above value of p , $\Lambda < 0$. For $R > 8R_1$ and $y \in Q(2R/3, 2R/3) \setminus Q(R/3, R_1/2)$ by Lemma 2.3 and using the fact that $0 \vee (\frac{3\alpha}{2} - 2) < p < \frac{\alpha}{2} < 1$, we obtain

$$\begin{aligned} & (\Delta + \widehat{\Delta}^{\alpha/2}) \left(h_{\alpha/2}(y) - R_1^{\alpha/2-p} h_p(y) \right) \\ & \geq -\frac{\alpha}{2} \left(1 - \frac{\alpha}{2}\right) (y_d)^{\frac{\alpha}{2}-2} - c_1 R^{-\alpha/2} - R_1^{\alpha/2-p} p(p-1) (y_d)^{p-2} + |\Lambda| R_1^{\alpha/2-p} (y_d)^{p-\alpha} \\ & = (y_d)^{p-\alpha} \left(|\Lambda| R_1^{\alpha/2-p} + p(1-p) R_1^{\alpha/2-p} (y_d)^{\alpha-2} - \frac{\alpha}{2} \left(1 - \frac{\alpha}{2}\right) (y_d)^{\frac{3\alpha}{2}-2-p} \right) - c_1 R^{-\alpha/2} \\ & \geq (y_d)^{p-\alpha} \left(|\Lambda| R_1^{\alpha/2-p} - \frac{\alpha}{2} \left(1 - \frac{\alpha}{2}\right) (R_1/2)^{\frac{3\alpha}{2}-2-p} \right) - c_1 R^{-\alpha/2}. \end{aligned}$$

Now, using (2.11), we have, for $y \in Q(2R/3, 2R/3) \setminus Q(R/3, R_1/2)$

$$(\Delta + \widehat{\Delta}^{\alpha/2}) \left(h_{\alpha/2}(y) - R_1^{\alpha/2-p} h_p(y) \right) \geq -c_1 R^{-\alpha/2}. \quad (2.12)$$

Moreover, for $y \in Q(R, R_1)$,

$$(h_{\alpha/2} - R_1^{\alpha/2-p} h_p)(y) = y_d^{\alpha/2} (1 - (R_1/y_d)^{\alpha/2-p}) \leq 0. \quad (2.13)$$

Let g be a nonnegative smooth radial function with compact support in \mathbb{R}^d such that $g(x) = 0$ for $|x| > 1$ and $\int_{\mathbb{R}^d} g(x) dx = 1$. For $k \geq 1$, define $g_k(x) = 2^{kd} g(2^k x)$. Define

$$u_k(z) := g_k * \left(h_{\alpha/2} - R_1^{\alpha/2-p} h_p \right)(z) := \int_{\mathbb{R}^d} g_k(y) (h_{\alpha/2} - R_1^{\alpha/2-p} h_p)(z - y) dy \in C_c^\infty(\mathbb{R}^d).$$

Let $Q_{R,k} := \{z \in \mathbb{H} : \text{dist}(z, Q(R, R)) < 2^{-k}\}$ and $A_k = \{x \in \mathbb{H} : x_d \in (R_1 - 2^{-k}, R_1]\}$. Note that $u_k = 0$ on $Q_{R,k}^c$ and by (2.13), for k sufficiently large so that $2^{-k} < R_1/3$,

$$u_k(z) \leq 0 \quad \text{for } z_d \leq R_1 - 2^{-k}, \quad (2.14)$$

and for $z \in V_R$, by (2.12),

$$(\Delta + \Delta^{\alpha/2}) u_k(z) = (\Delta + \widehat{\Delta}^{\alpha/2}) u_k(z) = g_k * (\Delta + \widehat{\Delta}^{\alpha/2}) (h_{\alpha/2} - R_1^{\alpha/2-p} h_p)(z) \geq -c_1 R^{-\alpha/2}. \quad (2.15)$$

Therefore, using (2.3) and (2.13)–(2.15), we have that, for any $x \in V_R$,

$$\begin{aligned}
u_k(x) &= -\mathbb{E}_x \left[\int_0^{\tau_{V_R}^1} (\Delta + \Delta^{\alpha/2}) u_k(X_t^1) dt \right] + \mathbb{E}_x \left[u_k(X_{\tau_{V_R}^1}^1) \right] \\
&\leq c_1 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \mathbb{E}_x \left[u_k(X_{\tau_{V_R}^1}^1) : X_{\tau_{V_R}^1}^1 \in Q_{R,k} \setminus Q(R, R_1) \right] + \mathbb{E}_x \left[u_k(X_{\tau_{V_R}^1}^1) : X_{\tau_{V_R}^1}^1 \in A_k \right] \\
&\leq c_1 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \sup_{z \in A_k} |u_k(z)| \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in A_k \right) \\
&\quad + \left(\sup_{z \in Q_{R,k} \setminus Q(R, R_1)} u_k(z) \right) \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q_{R,k} \setminus Q(R, R_1) \right) \\
&\leq c_1 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \sup_{z \in A_k} |u_k(z)| + \left(\sup_{z \in Q_{R,k}} h_{\alpha/2}(z) \right) \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q_{R,k} \setminus Q(R, R_1) \right) \\
&\leq c_1 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \sup_{z \in A_k} |u_k(z)| + R^{\alpha/2} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q_{R,k} \setminus Q(R, R_1) \right).
\end{aligned}$$

Since $h_{\alpha/2}(z) - R_1^{\alpha/2-p} h_p(z) = 0$ on $z_d = R_1$, $\lim_{k \rightarrow \infty} \sup_{z \in A_k} |u_k(z)| = 0$. Observe that $Q_k(R, R) \setminus Q(R, R_1)$ decreases to $\overline{Q(R, R)} \setminus Q(R, R_1)$ as $k \rightarrow \infty$. We have

$$\begin{aligned}
\lim_{k \rightarrow \infty} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q_{R,k} \setminus Q_1(R, R_1) \right) &= \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in \overline{Q(R, R)} \setminus Q(R, R_1) \right) \\
&= \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R_1) \right),
\end{aligned}$$

where the last equality is due to an application of Lévy system and the fact that $\partial Q(R, R)$ has zero Lebesgue measure. Therefore for $x \in Q(R/2, R/2) \setminus Q(R/2, 2R_1)$, since $x_d \geq 2R_1$,

$$\begin{aligned}
(1 - 2^{p-\alpha/2})(x_d)^{\alpha/2} &\leq (x_d)^{\alpha/2} (1 - (R_1/x_d)^{\alpha/2-p}) = \lim_{k \rightarrow \infty} u_k(x) \\
&\leq c_1 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + R^{\alpha/2} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R_1) \right),
\end{aligned}$$

which implies

$$(x_d)^{\alpha/2} \leq c_1 \frac{R^{-\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{E}_x[\tau_{V_R}^1] + \frac{R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R_1) \right). \quad (2.16)$$

Now take a non-negative function ϕ in $C_c^\infty(\mathbb{R}^d)$ such that $0 \leq \phi \leq 1$,

$$\phi(y) = \begin{cases} 0 & \text{if } |\tilde{y}| < 1/4 \text{ or } |y_d| > 2, \\ 1 & \text{if } 1/2 \leq |\tilde{y}| \leq 2 \text{ and } |y_d| < 1, \\ 0 & \text{if } |\tilde{y}| > 3, \end{cases}$$

and that $\sum_{i,j} |\frac{\partial^2}{\partial y_i \partial y_j} \phi|$ is uniformly bounded. Define $\phi_R(y) = \phi(\frac{y}{R})$. Then we have $0 \leq \phi_R \leq 1$,

$$\phi_R(y) = \begin{cases} 0 & \text{if } |\tilde{y}| < R/4 \text{ or } |y_d| > 2R, \\ 1 & \text{if } R/2 \leq |\tilde{y}| \leq 2R \text{ and } |y_d| < R, \\ 0 & \text{if } |\tilde{y}| > 3R, \end{cases} \quad (2.17)$$

and

$$\sup_{y \in \mathbb{R}^d} \sum_{i,j} \left| \frac{\partial^2}{\partial y_i \partial y_j} \phi_R(y) \right| < c_2 R^{-2}.$$

Using this inequality, by the argument leading to (2.4), we get

$$\sup_{k \geq 1} \sup_{z \in \mathbb{R}^d} \left| (\Delta + \Delta^{\alpha/2}) \phi_R(z) \right| \leq c_2 R^{-2} + c_3 R^{-\alpha}.$$

Thus, by this and Lemma 2.3, for $R > 8R_1$ and $y \in Q(2R/3, 2R/3)$, we obtain

$$(\Delta + \widehat{\Delta}^{\alpha/2}) \left(h_{\alpha/2}(y) + \frac{2R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \phi_R(y) \right) \leq -\frac{\alpha}{2} \left(1 - \frac{\alpha}{2} \right) (y_d)^{\frac{\alpha}{2}-2} + c_4 R^{\alpha/2} R^{-\alpha} \leq c_4 R^{-\alpha/2}. \quad (2.18)$$

For any $k \geq 1$, define

$$v_k(z) := g_k * \left(h_{\alpha/2} + \frac{2R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \phi_R \right)(z) \in C_c^\infty(\mathbb{R}^d).$$

Put $\Omega_R := Q(R, R/2) \setminus (Q(R, R_1) \cup Q(R/2, R/2))$. By (2.18), we have $(\Delta + \Delta^{\alpha/2}) v_k(y) \leq c_4 R^{-\alpha/2}$ for all $y \in V_R$. Thus, using this and (2.3), we have that for any $k \geq 1$ and $x \in Q(R/4, R/2) \setminus Q(R/4, 2R_1)$

$$\begin{aligned} v_k(x) &= -\mathbb{E}_x \left[\int_0^{\tau_{V_R}^1} (\Delta + \Delta^{\alpha/2}) v_k(X_t^1) dt \right] + \mathbb{E}_x \left[v_k(X_{\tau_{V_R}^1}^1) \right] \\ &\geq -c_4 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \mathbb{E}_x \left[v_k(X_{\tau_{V_R}^1}^1) : X_{\tau_{V_R}^1}^1 \in \Omega_R \right]. \end{aligned}$$

Letting $k \rightarrow \infty$ and using (2.17), we get that for any $x \in Q(R/4, R/2) \setminus Q(R/4, 2R_1)$ (where $\phi_R(x) = 0$),

$$\begin{aligned} (x_d)^{\alpha/2} &= \left(h_{\alpha/2} + \frac{2R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \phi_R \right)(x) = \lim_{k \rightarrow \infty} v_k(x) \\ &\geq -c_4 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \mathbb{E}_x \left[\left(h_{\alpha/2} + \frac{2R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \phi_R \right) (X_{\tau_{V_R}^1}^1) : X_{\tau_{V_R}^1}^1 \in \Omega_R \right] \\ &\geq -c_4 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \frac{2R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in \Omega_R \right). \end{aligned} \quad (2.19)$$

Combining (2.16) and (2.19), we get

$$\begin{aligned} (x_d)^{\alpha/2} &\leq \frac{c_1 R^{-\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{E}_x[\tau_{V_R}^1] + \frac{R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R_1) \right) \\ &= \frac{c_1 R^{-\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{E}_x[\tau_{V_R}^1] + \frac{R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R/2) \right) \\ &\quad + \frac{R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in \Omega_R \right) \\ &\leq \frac{c_1 R^{-\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{E}_x[\tau_{V_R}^1] + \frac{R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R/2) \right) \\ &\quad + \frac{1}{2} \left(c_4 R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + (x_d)^{\alpha/2} \right). \end{aligned}$$

Therefore, we conclude that

$$(x_d)^{\alpha/2} \leq \left(\frac{2c_1}{1 - 2^{p-\alpha/2}} + c_4 \right) R^{-\alpha/2} \mathbb{E}_x[\tau_{V_R}^1] + \frac{2R^{\alpha/2}}{1 - 2^{p-\alpha/2}} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R/2) \right). \quad (2.20)$$

On the other hand, by the Lévy system of X^1 ,

$$\begin{aligned} \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, R/2) \right) &\geq \mathbb{P}_x \left(X_{\tau_{V_R}^1}^1 \in Q(R, R) \setminus Q(R, 3R/4) \right) \\ &= \mathbb{E}_x \left[\int_0^{\tau_{V_R}^1} \left(\int_{Q(R, R) \setminus Q(R, 3R/4)} J^1(X_s^1, z) dz \right) ds \right] \geq c_5 R^{-\alpha} \mathbb{E}_x[\tau_{V_R}^1]. \end{aligned}$$

This together with (2.20) establishes the lemma. \square

3 Upper bound heat kernel estimates on half-space

In this section we will establish the desired large time upper bound for $p_{\mathbb{H}}^1(t, x, y)$.

Lemma 3.1 *For any $t_0 > 0$ and $R > 0$, there exists $c = c(\alpha, t_0, R) > 1$ such that for $t \geq t_0$ and $x \in \mathbb{H}$ with $\delta_{\mathbb{H}}(x) = x_d \geq R$, we have*

$$\mathbb{P}_x(\tau_{\mathbb{H}}^1 > t) \leq c \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right).$$

Proof. Clearly, we can assume $R \leq t_0^{1/\alpha}$ and we only need to show the theorem for $R \leq \delta_H(x) < t^{1/\alpha}$. Let $u(x) = (x_d^+)^{\alpha/2} + 1$ and $U(r) := \{x \in \mathbb{H}; x_d < r\}$. By (2.8), for every $x \in \mathbb{H}$ with $\delta_{\mathbb{H}}(x) \geq R$,

$$(\Delta + \hat{\Delta}^{\alpha/2})u(x) = -\frac{\alpha}{2}(1 - \frac{\alpha}{2})(x_d)^{\alpha/2-2} < 0.$$

Using the same approximation argument as in the proof of Lemma 2.4 with $u_k(z) := (g_k * u)(z)$ where g_k is the function defined in the proof of Lemma 2.4 and letting $k \rightarrow \infty$, we see that for $x \in \mathbb{H}$ with $r > \delta_{\mathbb{H}}(x) = x_d > R$,

$$(1 + R^{-\alpha/2})x_d^{\alpha/2} \geq x_d^{\alpha/2} + 1 = u(x) \geq \mathbb{E}_x \left[u \left(X_{\tau_{U(r)}^1}^1 \right) \right] \geq r^{\alpha/2} \mathbb{P}_x \left(X_{\tau_{U(r)}^1}^1 \in \mathbb{H} \setminus U(r) \right).$$

Applying this and Proposition 2.1, we get that for $R < \delta_{\mathbb{H}}(x) < t^{1/\alpha}$.

$$\begin{aligned} \mathbb{P}_x(\tau_{\mathbb{H}}^1 > t) &\leq \mathbb{P}_x(\tau_{U(t^{1/\alpha})}^1 > t) + \mathbb{P}_x \left(X_{\tau_{U(t^{1/\alpha})}^1}^1 \in \mathbb{H} \setminus U(t^{1/\alpha}) \right) \\ &\leq \frac{1}{t} \mathbb{E}_x[\tau_{U(t^{1/\alpha})}^1] + (1 + R^{-\alpha/2}) \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \\ &\leq c_1 \frac{1}{t} (t^{1/\alpha} \wedge t^{1/2}) (\delta_{\mathbb{H}}(x)^{\alpha/2} \wedge \delta_{\mathbb{H}}(x)) + (1 + R^{-\alpha/2}) \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \leq c_2 \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}}. \end{aligned}$$

\square

Lemma 3.2 *For every t_0 and $R > 0$, there exists $c = c(\alpha, t_0, R) > 1$ such that for every $(t, x, y) \in [t_0, \infty) \times \mathbb{H} \times \mathbb{H}$ with $\delta_{\mathbb{H}}(x) \geq R$,*

$$p_{\mathbb{H}}^1(t, x, y) \leq ct^{-d/\alpha} \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right).$$

Proof. By the semigroup property and symmetry,

$$\begin{aligned} p_{\mathbb{H}}^1(t, x, y) &= \int_{\mathbb{H}} \int_{\mathbb{H}} p_{\mathbb{H}}^1(t/3, x, z) p_{\mathbb{H}}^1(t/3, z, w) p_{\mathbb{H}}^1(t/3, w, y) dz dw \\ &\leq \left(\sup_{z, w \in \mathbb{R}^d} p^1(t/3, z, w) \right) \mathbb{P}_x(\tau_{\mathbb{H}}^1 > t/3) \mathbb{P}_y(\tau_{\mathbb{H}}^1 > t/3). \end{aligned}$$

Now the lemma follows from Theorem 1.1 and Lemma 3.1. \square

The next lemma and its proof are given in [5] (also see [3, Lemma 2] and [4, Lemma 2.2]).

Lemma 3.3 *Suppose that U_1, U_3, E are open subsets of \mathbb{R}^d with $U_1, U_3 \subset E$ and $\text{dist}(U_1, U_3) > 0$. Let $U_2 := E \setminus (U_1 \cup U_3)$. If $x \in U_1$ and $y \in U_3$, then for all $t > 0$,*

$$p_E^1(t, x, y) \leq \mathbb{P}_x \left(X_{\tau_{U_1}^1}^1 \in U_2 \right) \left(\sup_{s < t, z \in U_2} p_E^1(s, z, y) \right) + \mathbb{E}_x [\tau_{U_1}^1] \left(\sup_{u \in U_1, z \in U_3} J^1(u, z) \right). \quad (3.1)$$

Lemma 3.4 *Suppose that $t_0, R > 0$. There exists $c = c(\alpha, t_0, R) > 0$ such that for every $(t, x, y) \in [t_0, \infty) \times \mathbb{H} \times \mathbb{H}$ with $\delta_{\mathbb{H}}(x) \geq R$,*

$$p_{\mathbb{H}}^1(t, x, y) \leq c \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x - y|^{d+\alpha}} \right).$$

Proof. By Theorem 1.1, Proposition 1.2 and Lemma 3.2, without loss of generality we can assume $R = t_0^{1/\alpha}$ and it is enough to prove the lemma for $t_0^{1/\alpha} \leq \delta_{\mathbb{H}}(x) \leq (16)^{-1} t^{1/\alpha}$ and $|x - y| \geq t^{1/\alpha}$. Let $x_0 = (\tilde{x}, 0)$, $U_1 := B(x_0, 8^{-1} t^{1/\alpha}) \cap \mathbb{H}$, $U_3 := \{z \in \mathbb{H} : |z - x| > |x - y|/2\}$ and $U_2 := \mathbb{H} \setminus (U_1 \cup U_3)$.

Let $X^1 = (X^{1,1}, \dots, X^{1,d})$ and, for any open interval (β, γ) in \mathbb{R} , let $\hat{\tau}_{(\beta, \gamma)} := \inf\{t > 0 : X^{1,d} \notin (\beta, \gamma)\}$. Note that, by Proposition 2.1 and the assumption that $16^{-1} t^{1/\alpha} \geq \delta_{\mathbb{H}}(x) = x_d \geq t_0^{1/\alpha}$, we have

$$\mathbb{E}_x[\tau_{U_1}^1] \leq \mathbb{E}_{x_d}[\hat{\tau}_{(0, t^{1/\alpha})}] \leq c_1 \sqrt{t} x_d^{\alpha/2} = c_1 \sqrt{t} \delta_{\mathbb{H}}(x)^{\alpha/2}. \quad (3.2)$$

Since

$$|z - x| > \frac{|x - y|}{2} \geq \frac{1}{2} t^{1/\alpha} \quad \text{for } z \in U_3,$$

$U_1 \cap U_3 = \emptyset$ and, if $u \in U_1$ and $z \in U_3$, then

$$|u - z| \geq |z - x| - |x_0 - x| - |x_0 - u| \geq |z - x| - 4^{-1} t^{1/\alpha} \geq \frac{1}{2} |z - x| \geq \frac{1}{4} |x - y|. \quad (3.3)$$

Thus,

$$\sup_{u \in U_1, z \in U_3} J^1(u, z) \leq \sup_{(u, z): |u - z| \geq \frac{1}{4} |x - y|} J^1(u, z) \leq c_3 |x - y|^{-d-\alpha}. \quad (3.4)$$

If $z \in U_2$,

$$\frac{3}{2}|x-y| \geq |x-y| + |x-z| \geq |z-y| \geq |x-y| - |x-z| \geq \frac{|x-y|}{2} \geq 2^{-1}t^{1/\alpha}. \quad (3.5)$$

By Theorem 1.1 and (3.5),

$$\begin{aligned} \sup_{s \leq t, z \in U_2} p^1(s, z, y) &\leq c_4 \sup_{s \leq t, |z-y| \geq |x-y|/2} (sJ^1(z, y)) + c_4 \sup_{s \leq t, s^{1/2} \geq |z-y| \geq |x-y|/2} s^{-d/2} \\ &\quad + c_4 \sup_{\substack{s \leq t, s^{1/2} \leq |z-y|, \\ 1 \geq |z-y| \geq |x-y|/2}} s^{-d/2} e^{-c_5|z-y|^2/s} \\ &\leq c_6 t |x-y|^{-d-\alpha} + 2^{d+\alpha} c_4 \left(\sup_{s \leq t} \frac{s^{\alpha/2}}{|x-y|^{d+\alpha}} \right) \\ &\quad + c_4 \left(\sup_{a \geq 1} a^{-d/2} e^{-c_5 a} \right) \sup_{1 \geq |z-y| \geq |x-y|/2} |z-y|^{-d} \\ &\leq c_7 t |x-y|^{-d-\alpha} + c_8 \sup_{1 \geq |z-y| \geq |x-y|/2} \frac{|z-y|^\alpha}{|x-y|^{d+\alpha}} \leq c_9 t |x-y|^{-d-\alpha}. \quad (3.6) \end{aligned}$$

Applying Lemma 3.3, (3.2), (3.4) and (3.6), we obtain,

$$\begin{aligned} p_{\mathbb{H}}^1(t, x, y) &\leq c_{10} \mathbb{E}_x[\tau_{U_1}^1] |x-y|^{-d-\alpha} + c_{11} \mathbb{P}_x(X_{\tau_{U_1}^1}^1 \in U_2) t |x-y|^{-d-\alpha} \\ &\leq c_{12} \sqrt{t} \delta_{\mathbb{H}}(x)^{\alpha/2} |x-y|^{-d-\alpha} + c_{11} \mathbb{P}_x(X_{\tau_{U_1}^1}^1 \in U_2) t |x-y|^{-d-\alpha}. \end{aligned}$$

Finally, applying Theorem 2.2 with $U = U_1$ and $r = 8^{-1}t^{1/\alpha} \geq 2t_0^{1/\alpha}$, we have

$$\mathbb{P}_x(X_{\tau_{U_1}^1}^1 \in U_2) \leq \mathbb{P}_x(X_{\tau_{U_1}^1}^1 \in B(x_0, 8^{-1}t^{1/\alpha})^c) \leq c_{14} \frac{1}{t} \int_{U_1} G_{U_1}^1(x, y) dy = c_{14} \frac{1}{t} \mathbb{E}_x[\tau_{U_1}^1].$$

Now applying (3.2), we have proved the lemma. \square

Lemma 3.5 *For every $R > 0$ and $t_0 > 0$, there exists a constant $c = c(R, \alpha, t_0)$ such that for all $(t, x, y) \in [t_0, \infty) \times \mathbb{H} \times \mathbb{H}$ with $\delta_{\mathbb{H}}(x) \wedge \delta_{\mathbb{H}}(y) \geq R$.*

$$p_{\mathbb{H}}^1(t, x, y) \leq c \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right).$$

Proof. By Lemma 3.4 and Theorem 1.1, we only need to prove the theorem for $\delta_{\mathbb{H}}(x) \vee \delta_{\mathbb{H}}(y) \leq t^{1/\alpha}$. Denote by $q(t, x, y)$ the transition density of the α -stable process Y in \mathbb{R}^d . By Lemma 3.4 and the lower bound estimate of $q(t, x, y)$, there is a constant $c_1 > 0$ so that

$$p_{\mathbb{H}}^1(t/2, x, z) \leq c_1 \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) q(t/2, x, z) \quad \text{and} \quad p_{\mathbb{H}}^1(t/2, z, y) \leq c_1 \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) q(t/2, y, z).$$

Thus, by semigroup property and the upper bound estimate of $q(t, x, y)$,

$$p_{\mathbb{H}}^1(t, x, y) = \int_{\mathbb{H}} p_{\mathbb{H}}^1(t/2, x, z) p_{\mathbb{H}}^1(t/2, z, y) dz$$

$$\begin{aligned}
&\leq c_2^2 \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \int_{\mathbb{H}} q(t/2, x, z) q(t/2, y, z) dz \\
&\leq c_2^2 \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) q(t, x, y) \\
&\leq c_3 \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right).
\end{aligned}$$

□

Theorem 3.6 *Let t_0 be a positive constant. Then there exists a constant $c = c(\alpha, t_0) > 0$ such that for all $t \in [t_0, \infty)$ and $x, y \in \mathbb{H}$,*

$$p_{\mathbb{H}}^1(t, x, y) \leq c \left(\frac{\delta_{\mathbb{H}}(x) \wedge \delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y) \wedge \delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right).$$

Proof. Let x_0 and y_0 be as in (1.15). By the semigroup property and (1.17), we have

$$\begin{aligned}
p_{\mathbb{H}}^1(t, x, y) &= \int_{\mathbb{H}} \int_{\mathbb{H}} p_{\mathbb{H}}^1(t_0, x, z) p_{\mathbb{H}}^1(t - 2t_0, z, w) p_{\mathbb{H}}^1(t_0, w, y) dz dw \\
&\asymp (1 \wedge \delta_{\mathbb{H}}(x)) (1 \wedge \delta_{\mathbb{H}}(y)) \int_{\mathbb{H}} \int_{\mathbb{H}} p_{\mathbb{H}}^1(t_0, x_0, z) p_{\mathbb{H}}^1(t - 2t_0, z, w) p_{\mathbb{H}}^1(t_0, w, y_0) dz dw \\
&= (1 \wedge \delta_{\mathbb{H}}(x)) (1 \wedge \delta_{\mathbb{H}}(y)) p_{\mathbb{H}}^1(t, x_0, y_0).
\end{aligned} \tag{3.7}$$

By Lemma 3.5 and the fact $|x_0 - y_0| = |x - y|$, we have

$$p_{\mathbb{H}}^1(t, x_0, y_0) \leq c_1 \left(\frac{\delta_{\mathbb{H}}(x_0)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y_0)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right).$$

This together with Lemma 1.11 (with $a = 1$ there) and (3.7) proves the theorem. □

4 Lower bound heat kernel estimates on half-space

In this section we establish the desired sharp large time lower bound on $p_{\mathbb{H}}^1(t, x, y)$. We will use some ideas from [3, 5].

Lemma 4.1 *For any positive constant t_0 , there exists $c = c(t_0, \alpha) > 0$ such that for any $t \geq t_0$ and $y \in \mathbb{R}^d$,*

$$\mathbb{P}_y \left(\tau_{B(y, 8^{-1}t^{1/\alpha})}^1 > t/3 \right) \geq c.$$

Proof. By [10, Proposition 6.2], there exists $\varepsilon = \varepsilon(t_0, \alpha) > 0$ such that for every $t \geq t_0$,

$$\inf_{y \in \mathbb{R}^d} \mathbb{P}_y \left(\tau_{B(y, 16^{-1}t^{1/\alpha})}^1 > \varepsilon t \right) \geq \frac{1}{2}.$$

Suppose $\varepsilon < \frac{1}{3}$, then by the parabolic Harnack inequality in [10, 22],

$$c_1 p_{B(y, 8^{-1}t^{1/\alpha})}^1(\varepsilon t, y, w) \leq p_{B(y, 8^{-1}t^{1/\alpha})}^1(t/3, y, w) \quad \text{for } w \in B(y, 16^{-1}t^{1/\alpha}),$$

where the constant $c_1 = c_1(t_0, \alpha) > 0$ is independent of $y \in \mathbb{R}^d$. Thus

$$\begin{aligned} \mathbb{P}_y \left(\tau_{B(y, 8^{-1}t^{1/\alpha})}^1 > t/3 \right) &= \int_{B(y, 8^{-1}t^{1/\alpha})} p_{B(y, 8^{-1}t^{1/\alpha})}^1(t/3, y, w) dw \\ &\geq c_1 \int_{B(y, 16^{-1}t^{1/\alpha})} p_{B(y, 8^{-1}t^{1/\alpha})}^1(\varepsilon t, y, w) dw \geq \frac{c_1}{2}. \end{aligned}$$

□

The next result holds for any symmetric discontinuous Hunt process that possesses a transition density and whose Lévy system admitting jumping density kernel. Its proof is the same as that of [6, Lemma 3.3] and so it is omitted here.

Lemma 4.2 *Suppose that U_1, U_2, U are open subsets of \mathbb{R}^d with $U_1, U_2 \subset U$ and $\text{dist}(U_1, U_2) > 0$. If $x \in U_1$ and $y \in U_2$, then for all $t > 0$,*

$$p_U^1(t, x, y) \geq t \mathbb{P}_x(\tau_{U_1}^1 > t) \mathbb{P}_y(\tau_{U_2}^1 > t) \inf_{u \in U_1, z \in U_2} J^1(u, z). \quad (4.1)$$

Lemma 4.3 *Suppose that $t_0 > 0$. There exists $c = c(t_0, \alpha) > 0$ such that for all $t \geq t_0$ and $u, v \in \mathbb{R}^d$ with $|u - v| \geq t^{1/\alpha}/2$,*

$$p_{B(u, t^{1/\alpha}) \cup B(v, t^{1/\alpha})}^1(t/3, u, v) \geq c t |u - v|^{-d-\alpha}.$$

Proof. Let $U = B(u, t^{1/\alpha}) \cup B(v, t^{1/\alpha})$. With $U_1 = B(u, t^{1/\alpha}/8)$ and $U_2 = B(v, t^{1/\alpha}/8)$, we have by Lemma 4.2 that

$$p_U^1(t/3, u, v) \geq \frac{t}{3} \mathbb{P}_u(\tau_{U_1}^1 > t/3) \left(\inf_{w \in U_1, z \in U_2} j^1(|w - z|) \right) \mathbb{P}_v(\tau_{U_2}^1 > t/3).$$

Moreover, $|w - z| \leq |u - v| + |w - u| + |z - v| \leq |u - v| + t^{1/\alpha}/4 \leq \frac{3}{2}|u - v|$. Thus by Lemma 4.1,

$$\begin{aligned} p_{B(u, t^{1/\alpha}) \cup B(v, t^{1/\alpha})}^1(t/3, u, v) &\geq \frac{t}{3} \left(\mathbb{P}_0(\tau_{B(0, t^{1/\alpha}/8)}^1 > t/3) \right)^2 \left(\inf_{w \in U_1, z \in U_2} j^1(|w - z|) \right) \\ &\geq c_1 t |u - v|^{-d-\alpha}. \end{aligned}$$

□

The next result follows from [22, Proposition 3.4].

Lemma 4.4 *There exist $R_2 = R_2(\alpha) > 1$ and $c = c(\alpha) > 0$ such that for all $t \geq R_2^\alpha$,*

$$\inf_{x, y \in B(0, 6t^{1/\alpha})} p_{B(0, 12t^{1/\alpha})}^1(t/3, x, y) \geq c t^{-d/\alpha}.$$

For the remainder of this section, we define $R_3 := R_1 \vee R_2$, where $R_1 > 0$ is the constant in Lemma 2.4. For any $x \in \mathbb{R}^d$ and $a, b > 0$, we define

$$Q_x(a, b) := \{y \in \mathbb{H} : |\tilde{y} - \tilde{x}| < a, y_d < b\}.$$

Lemma 4.5 *There is a positive constant $c = c(\alpha)$ such that for all $(t, x) \in ((4R_1)^\alpha, \infty) \times \mathbb{H}$ with $2R_1 < \delta_{\mathbb{H}}(x) < t^{1/\alpha}/2$,*

$$\mathbb{P}_x(\tau_{Q_x(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3) \geq c \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}}.$$

Proof. Without loss of generality we assume that $\tilde{x} = \tilde{0}$ and let $Q(a, b) := Q_0(a, b)$. Let $V(t) := Q(t^{1/\alpha}/2, t^{1/\alpha}/2) \setminus Q(t^{1/\alpha}/2, R_1)$. By Lemma 2.4, Lemma 4.1 and the strong Markov property,

$$\begin{aligned} & \mathbb{P}_x \left(\tau_{Q(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3 \right) \\ & \geq \mathbb{P}_x \left(\tau_{Q(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3, X_{\tau_{V(t)}^1}^1 \in Q(t^{1/\alpha}, t^{1/\alpha}) \setminus Q(t^{1/\alpha}, t^{1/\alpha}/2) \right) \\ & = \mathbb{E}_x \left[\mathbb{P}_{X_{\tau_{V(t)}^1}^1} \left(\tau_{Q(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3 \right) : X_{\tau_{V(t)}^1}^1 \in Q(t^{1/\alpha}, t^{1/\alpha}) \setminus Q(t^{1/\alpha}, t^{1/\alpha}/2) \right] \\ & \geq \mathbb{E}_x \left[\mathbb{P}_{X_{\tau_{V(t)}^1}^1} \left(\tau_{B(X_{\tau_{V(t)}^1}^1, 4^{-1}t^{1/\alpha})}^1 > t/3 \right) : X_{\tau_{V(t)}^1}^1 \in Q(t^{1/\alpha}, t^{1/\alpha}) \setminus Q(t^{1/\alpha}, t^{1/\alpha}/2) \right] \\ & \geq c_1 \mathbb{P}_x \left(X_{\tau_{V(t)}^1}^1 \in Q(t^{1/\alpha}, t^{1/\alpha}) \setminus Q(t^{1/\alpha}, 2^{-1}t^{1/\alpha}) \right) \geq c_2 \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}}. \end{aligned}$$

This proves the Lemma. \square

Lemma 4.6 *There is a positive constant $c = c(\alpha)$ such that for all $(t, x, y) \in [(4R_3)^\alpha, \infty) \times \mathbb{H} \times \mathbb{H}$ with $\delta_{\mathbb{H}}(x) \wedge \delta_{\mathbb{H}}(y) \geq 2R_3$,*

$$p_{\mathbb{H}}^1(t, x, y) \geq c \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x - y|^{d+\alpha}} \right).$$

Proof. Fix $x, y \in \mathbb{H}$. Let $x_0 = (\tilde{x}, 0)$, $y_0 = (\tilde{y}, 0)$, $\xi_x := x + (\tilde{0}, 32t^{1/\alpha})$ and $\xi_y := y + (\tilde{0}, 32t^{1/\alpha})$. If $2R_3 \leq \delta_{\mathbb{H}}(x) < t^{1/\alpha}/2$, by Lemmas 4.1, 4.2 and 4.5,

$$\begin{aligned} & \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) du \\ & \geq t \mathbb{P}_x \left(\tau_{Q_x(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3 \right) \left(\inf_{\substack{v \in Q_x(2t^{1/\alpha}, 2t^{1/\alpha}) \\ w \in B(\xi_x, 4t^{1/\alpha})}} J^1(v, w) \right) \int_{B(\xi_x, 2t^{1/\alpha})} \mathbb{P}_u \left(\tau_{B(\xi_x, 4t^{1/\alpha})}^1 > t/3 \right) du \\ & \geq c_1 t \mathbb{P}_x \left(\tau_{Q_x(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3 \right) t^{-d/\alpha-1} \mathbb{P}_0 \left(\tau_{B(0, t^{1/\alpha}/8)}^1 > t/3 \right) |B(\xi_x, 2t^{1/\alpha})| \\ & \geq c_2 \mathbb{P}_x \left(\tau_{Q_x(2t^{1/\alpha}, 2t^{1/\alpha})}^1 > t/3 \right) \geq c_3 \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}}. \end{aligned}$$

On the other hand, if $\delta_{\mathbb{H}}(x) \geq t^{1/\alpha}/2 \geq 2R_3$, by Lemmas 4.1 and 4.2,

$$\begin{aligned}
& \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) du \\
& \geq t \mathbb{P}_x \left(\tau_{B(x, 8^{-1}t^{1/\alpha}) \cap \mathbb{H}}^1 > t/3 \right) \left(\inf_{\substack{v \in B(x_0, 2t^{1/\alpha}) \cap \mathbb{H} \\ w \in B(\xi_x, 4t^{1/\alpha})}} J^1(v, w) \right) \int_{B(\xi_x, 2t^{1/\alpha})} \mathbb{P}_u \left(\tau_{B(\xi_x, 4t^{1/\alpha})}^1 > t/3 \right) du \\
& \geq c_4 t \mathbb{P}_x \left(\tau_{B(x, 8^{-1}t^{1/\alpha})}^1 > t/3 \right) t^{-d/\alpha-1} \mathbb{P}_0 \left(\tau_{B(0, t^{1/\alpha}/8)}^1 > t/3 \right) |B(\xi_x, 2t^{1/\alpha})| \\
& \geq c_5 \mathbb{P}_x \left(\tau_{B(x, 8^{-1}t^{1/\alpha})}^1 > t/3 \right) \geq c_6.
\end{aligned}$$

Thus

$$\int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) du \geq c_7 \left(1 \wedge \frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \right), \quad (4.2)$$

and similarly,

$$\int_{B(\xi_y, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, y, u) du \geq c_7 \left(1 \wedge \frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \right). \quad (4.3)$$

Now we deal with the cases $|x - y| \geq 5t^{1/\alpha}$ and $|x - y| < 5t^{1/\alpha}$ separately.

Case 1: Suppose that $|x - y| \geq 5t^{1/\alpha}$. Note that by the semigroup property and Lemma 4.3,

$$\begin{aligned}
& p_{\mathbb{H}}^1(t, x, y) \\
& \geq \int_{B(\xi_y, 2t^{1/\alpha})} \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) p_{\mathbb{H}}^1(t/3, u, v) p_{\mathbb{H}}^1(t/3, v, y) dudv \\
& \geq \int_{B(\xi_y, 2t^{1/\alpha})} \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) p_{B(u, t^{1/\alpha}) \cup B(v, t^{1/\alpha})}^1(t/3, u, v) p_{\mathbb{H}}^1(t/3, v, y) dudv \\
& \geq c_8 t \left(\inf_{(u, v) \in B(\xi_x, 2t^{1/\alpha}) \times B(\xi_y, 2t^{1/\alpha})} |u - v|^{-d-\alpha} \right) \int_{B(\xi_y, 2t^{1/\alpha})} \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) p_{\mathbb{H}}^1(t/3, v, y) dudv.
\end{aligned}$$

It then follows from (4.2)–(4.3) that

$$p_{\mathbb{H}}^1(t, x, y) \geq c_9 t \left(\inf_{(u, v) \in B(\xi_x, 2t^{1/\alpha}) \times B(\xi_y, 2t^{1/\alpha})} |u - v|^{-d-\alpha} \right) \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right). \quad (4.4)$$

Using the assumption $|x - y| \geq 5t^{1/\alpha}$ we get that, for $u \in B(\xi_x, 2t^{1/\alpha})$ and $v \in B(\xi_y, 2t^{1/\alpha})$, $|u - v| \leq 4t^{1/\alpha} + |x - y| \leq 2|x - y|$. Hence

$$\inf_{(u, v) \in B(\xi_x, 2t^{1/\alpha}) \times B(\xi_y, 2t^{1/\alpha})} |u - v|^{-d-\alpha} \geq c_{10} |x - y|^{-d-\alpha}. \quad (4.5)$$

By (4.4) and (4.5), we conclude that for $|x - y| \geq 5t^{1/\alpha}$

$$p_{\mathbb{H}}^1(t, x, y) \geq c_{11} \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) t |x - y|^{-d-\alpha}.$$

Case 2: Suppose $|x - y| < 5t^{1/\alpha}$. In this case, for every $(u, v) \in B(\xi_x, 2t^{1/\alpha}) \times B(\xi_y, 2t^{1/\alpha})$, $|u - v| \leq 9t^{1/\alpha}$. Thus, using the fact that $\delta_{\mathbb{H}}(\xi_x) \wedge \delta_{\mathbb{H}}(\xi_y) \geq 32t^{1/\alpha}$, there exists $w_0 \in \mathbb{H}$ such that

$$B(\xi_x, 2t^{1/\alpha}) \cup B(\xi_y, 2t^{1/\alpha}) \subset B(w_0, 6t^{1/\alpha}) \subset B(w_0, 12t^{1/\alpha}) \subset \mathbb{H}. \quad (4.6)$$

Now, by the semigroup property and (4.6), we get

$$\begin{aligned} & p_{\mathbb{H}}^1(t, x, y) \\ & \geq \int_{B(\xi_y, 2t^{1/\alpha})} \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) p_{B(w_0, 8t^{1/\alpha})}^1(t/3, u, v) p_{\mathbb{H}}^1(t/3, v, y) dudv \\ & \geq \left(\inf_{u, v \in B(w_0, 6t^{1/\alpha})} p_{B(w_0, 12t^{1/\alpha})}^1(t/3, u, v) \right) \int_{B(\xi_y, 2t^{1/\alpha})} \int_{B(\xi_x, 2t^{1/\alpha})} p_{\mathbb{H}}^1(t/3, x, u) p_{\mathbb{H}}^1(t/3, v, y) dudv. \end{aligned}$$

It then follows from (4.2)–(4.3) and Lemma 4.4 that

$$p_{\mathbb{H}}^1(t, x, y) \geq c_{12} \left(\frac{\delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) t^{-d/\alpha}.$$

Combining these two cases, we have proved the theorem. \square

Theorem 4.7 *There exists a positive constant $c = c(\alpha)$ such that for all $t \in [(4R_3)^\alpha, \infty)$ and $x, y \in \mathbb{H}$,*

$$p_{\mathbb{H}}^1(t, x, y) \geq c \left(1 \wedge \frac{\delta_{\mathbb{H}}(x) \wedge \delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y) \wedge \delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x - y|^{d+\alpha}} \right).$$

Proof. Let $t_0 = (4R_3)^2 > (4R_3)^\alpha$ and let x_0 and y_0 be as in (1.15). By the semigroup property and (1.17) we have

$$\begin{aligned} p_{\mathbb{H}}^1(t, x, y) &= \int_{\mathbb{H}} \int_{\mathbb{H}} p_{\mathbb{H}}^1(t_0, x, z) p_{\mathbb{H}}^1(t - 2t_0, z, w) p_{\mathbb{H}}^1(t_0, w, y) dz dw \\ &\asymp (1 \wedge \delta_{\mathbb{H}}(x)) (1 \wedge \delta_{\mathbb{H}}(y)) \int_{\mathbb{H}} \int_{\mathbb{H}} p_{\mathbb{H}}^1(t_0, x_0, z) p_{\mathbb{H}}^1(t - 2t_0, z, w) p_{\mathbb{H}}^1(t_0, w, y_0) dz dw \\ &= (1 \wedge \delta_{\mathbb{H}}(x)) (1 \wedge \delta_{\mathbb{H}}(y)) p_{\mathbb{H}}^1(t, x_0, y_0). \end{aligned} \quad (4.7)$$

Since, $\delta_{\mathbb{H}}(x_0) \wedge \delta_{\mathbb{H}}(y_0) > t_0^{1/2} = 4R_3$, by Lemma 4.6 and the fact $|x_0 - y_0| = |x - y|$,

$$p_{\mathbb{H}}^1(t, x_0, y_0) \geq c_1 \left(\frac{\delta_{\mathbb{H}}(x_0)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(\frac{\delta_{\mathbb{H}}(y_0)^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x - y|^{d+\alpha}} \right).$$

The conclusion of the theorem now follows from the above inequality, Lemma 1.11 and (4.7). \square

5 Heat kernel estimates on half-space-like domains

In this section, we will establish the main result of this paper.

Combining Theorem 1.3(i), Theorems 3.6 and 4.7, we get that for every $T > 0$, there exist constants $c_i = c_i(\alpha, T) \geq 1$, $i = 1, 2$, such that for all $(t, x, y) \in (0, T] \times \mathbb{H} \times \mathbb{H}$,

$$\begin{aligned} & c_1^{-1} \left(1 \wedge \frac{\delta_{\mathbb{H}}(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-c_2|x-y|^2/t} + \left(\frac{t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) \\ & \leq p_{\mathbb{H}}^1(t, x, y) \leq c_1 \left(1 \wedge \frac{\delta_{\mathbb{H}}(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-|x-y|^2/(c_2 t)} + \left(\frac{t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) \end{aligned}$$

and for all $t \in [T, \infty)$ and x, y in H ,

$$\begin{aligned} & c_1^{-1} \left(1 \wedge \frac{\delta_{\mathbb{H}}(x) \wedge \delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y) \wedge \delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right) \\ & \leq p_{\mathbb{H}}^1(t, x, y) \leq c_1 \left(1 \wedge \frac{\delta_{\mathbb{H}}(x) \wedge \delta_{\mathbb{H}}(x)^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y) \wedge \delta_{\mathbb{H}}(y)^{\alpha/2}}{\sqrt{t}} \right) \left(t^{-d/\alpha} \wedge \frac{t}{|x-y|^{d+\alpha}} \right). \end{aligned}$$

Now using (1.12), we established Theorem 1.4 for $D = \mathbb{H}$ in the form of (1.7)–(1.8).

Theorem 5.1 *For every $T > 0$, there exist $c = c(\alpha, T) \geq 1$ and $C_3 = C_3(\alpha, T) \geq 1$ such that for all $a > 0$ and $(t, x, y) \in (0, a^{2\alpha/(\alpha-2)}T] \times \mathbb{H} \times \mathbb{H}$,*

$$\begin{aligned} & c^{-1} \left(1 \wedge \frac{\delta_{\mathbb{H}}(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-C_3|x-y|^2/t} + \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) \\ & \leq p_{\mathbb{H}}^a(t, x, y) \leq c \left(1 \wedge \frac{\delta_{\mathbb{H}}(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-|x-y|^2/(C_3 t)} + \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) \end{aligned}$$

and for all $t \in [a^{2\alpha/(\alpha-2)}T, \infty)$ and x, y in \mathbb{H} ,

$$\begin{aligned} & c^{-1} \left(1 \wedge \frac{\delta_{\mathbb{H}}(x) \wedge (a^{-1}\delta_{\mathbb{H}}(x))^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y) \wedge (a^{-1}\delta_{\mathbb{H}}(y))^{\alpha/2}}{\sqrt{t}} \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) \\ & \leq p_{\mathbb{H}}^a(t, x, y) \\ & \leq c \left(1 \wedge \frac{\delta_{\mathbb{H}}(x) \wedge (a^{-1}\delta_{\mathbb{H}}(x))^{\alpha/2}}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(y) \wedge (a^{-1}\delta_{\mathbb{H}}(y))^{\alpha/2}}{\sqrt{t}} \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right). \end{aligned}$$

Now we are in a position to establish the main result of this paper.

Proof of Theorem 1.4. Recall that that D is a half-space-like $C^{1,1}$ domain with $C^{1,1}$ characteristics (R_0, Λ_0) and $\mathbb{H}_b \subset D \subset \mathbb{H}$ for some $b > 0$ such that that the path distance in D is comparable to the Euclidean distance with characteristic λ_0 . Then we have the following trivial inequalities

$$p_{\mathbb{H}_b}^a(t, x, y) \leq p_D^a(t, x, y) \leq p_{\mathbb{H}}^a(t, x, y), \quad a > 0, (t, x, y) \in (0, \infty) \times \mathbb{H}_b \times \mathbb{H}_b. \quad (5.1)$$

Let $t_0 := 1 \vee b^2$. It follows from Theorem 1.3 that we only need to prove the theorem for $t > 3t_0$. Now we suppose $t > 3t_0$. For any $x, y \in D$, we define x_0 and y_0 as in (1.15).

By the semigroup property and Lemma 1.10, we have

$$\begin{aligned} p_D^a(t, x, y) &= \int_D \int_D p_D^a(t_0, x, z) p_D^a(t - 2t_0, z, w) p_D^a(t_0, w, y) dz dw \\ &\leq c_1 (1 \wedge \delta_D(x))(1 \wedge \delta_D(y)) \int_{D \times D} h_{1/(25C_2)}^a(t_0, x, z) p_D^a(t - 2t_0, z, w) h_{1/(25C_2)}^a(t_0, w, y) dz dw. \end{aligned}$$

It follows from Theorem 5.1 with $T = 1$ and (5.1),

$$\begin{aligned} p_D^a(t - 2t_0, z, w) &\leq p_{\mathbb{H}}^a(t - 2t_0, z, w) \\ &\leq c_2 \begin{cases} \left(1 \wedge \frac{\delta_{\mathbb{H}}(z)}{\sqrt{t-2t_0}}\right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(w)}{\sqrt{t-2t_0}}\right) \left((t - 2t_0)^{-d/2} e^{-|z-w|^2/(C_3(t-2t_0))} + \left(\frac{a^\alpha(t-2t_0)}{|z-w|^{d+\alpha}} \wedge (t - 2t_0)^{-d/2}\right)\right), \\ \quad \forall(t - 2t_0) \in (0, a^{2\alpha/(\alpha-2)}]; \\ \left(1 \wedge \frac{\delta_{\mathbb{H}}(z) \wedge (a^{-1}\delta_{\mathbb{H}}(z))^{\alpha/2}}{\sqrt{t-2t_0}}\right) \left(1 \wedge \frac{\delta_{\mathbb{H}}(w) \wedge (a^{-1}\delta_{\mathbb{H}}(w))^{\alpha/2}}{\sqrt{t-2t_0}}\right) \left((a^\alpha(t - 2t_0))^{-d/\alpha} \wedge \frac{a^\alpha(t-2t_0)}{|z-w|^{d+\alpha}}\right), \\ \quad \forall(t - 2t_0) \geq a^{2\alpha/(\alpha-2)} \end{cases} \end{aligned}$$

where C_3 is the constant in Theorem 5.1 with $T = 1$. Put $A = (C_3 \vee (25C_2))$ where C_2 is the constant in Theorem 1.3 with $T = t_0$. Applying Theorem 5.1 with $T = 1$ again, we get

$$p_D^a(t - 2t_0, z, w) \leq c_3 p_{\mathbb{H}}^a(t - 2t_0, A^{-2}z, A^{-2}w)$$

and so, by Theorem 1.3

$$\begin{aligned} &p_D^a(t, x, y) \\ &\leq c_4 (1 \wedge \delta_D(x))(1 \wedge \delta_D(y)) \int_{D \times D} h_{1/A^4}^a(t_0, x_0, z) p_{\mathbb{H}}^a(t - 2t_0, A^{-2}z, A^{-2}w) h_{1/A^4}^a(t_0, w, y_0) dz dw \\ &\leq c_5 (1 \wedge \delta_D(x))(1 \wedge \delta_D(y)) \int_{\mathbb{H}_{-b/2} \times \mathbb{H}_{-b/2}} \left(t_0^{-d/2} e^{-|x_0-z|^2/(A^4 t_0)} + \left(\frac{a^\alpha t_0}{|x_0 - z|^{d+\alpha}} \wedge t_0^{-d/2}\right)\right) \\ &\quad \times p_{\mathbb{H}}^a(t - 2t_0, A^{-2}z, A^{-2}w) \left(t_0^{-d/2} e^{-|w-y_0|^2/(A^4 t_0)} + \left(\frac{a^\alpha t_0}{|w - y_0|^{d+\alpha}} \wedge t_0^{-d/2}\right)\right) dz dw. \end{aligned}$$

Thus, by a change of variable, and using (5.1) and Theorem 1.3, the above is less than or equal to $(1 \wedge \delta_D(x))(1 \wedge \delta_D(y))$ times

$$\begin{aligned} &c_6 \int_{\mathbb{H}_{-b/(2A^2)} \times \mathbb{H}_{-b/(2A^2)}} (1 \wedge \delta_{\mathbb{H}_{-b/(2A^2)}}(z))(1 \wedge \delta_{\mathbb{H}_{-b/(2A^2)}}(A^{-2}x_0)) \\ &\quad \times \left(t_0^{-d/2} e^{-|x_0-z|^2/(A^4 t_0)} + \left(\frac{a^\alpha t_0}{|x_0 - z|^{d+\alpha}} \wedge t_0^{-d/2}\right)\right) p_{\mathbb{H}_{-b/(2A^2)}}^a(t - 2t_0, z, w) \\ &\quad \times (1 \wedge \delta_{\mathbb{H}_{-b/(2A^2)}}(A^{-2}y_0))(1 \wedge \delta_{\mathbb{H}_{-b/(2A^2)}}(w)) \left(t_0^{-d/2} e^{-|w-y_0|^2/(A^4 t_0)} + \left(\frac{a^\alpha t_0}{|w - y_0|^{d+\alpha}} \wedge t_0^{-d/2}\right)\right) dz dw \\ &\leq c_7 \int_{\mathbb{H}_{-b/(2A^2)} \times \mathbb{H}_{-b/(2A^2)}} p_{\mathbb{H}_{-b/(2A^2)}}^a(t_0, A^{-2}x_0, z) p_{\mathbb{H}_{-b/(2A^2)}}^a(t - 2t_0, z, w) p_{\mathbb{H}_{-b/(2A^2)}}^a(t_0, w, A^{-2}y_0) dz dw \\ &= c_7 p_{\mathbb{H}_{-b/(2A^2)}}^a(t, A^{-2}x_0, A^{-2}y_0). \end{aligned}$$

Now using (1.12) and Theorem 5.1 with $T = A^{-4}(1 \wedge M^{2\alpha/(2-\alpha)})t_0$, we get

$$p_D^a(t, x, y) \leq c_8 (1 \wedge \delta_D(x))(1 \wedge \delta_D(y)) p_{\mathbb{H}_{-b/2}}^{A^{2(\alpha-2)/\alpha} a}(A^4 t, x_0, y_0)$$

$$\begin{aligned}
&\leq c_9 \begin{cases} (1 \wedge \delta_D(x)) \left(\frac{\delta_{\mathbb{H}-b/2}(x_0)}{\sqrt{t}} \wedge 1 \right) (1 \wedge \delta_D(y)) \left(\frac{\delta_{\mathbb{H}-b/2}(y_0)}{\sqrt{t}} \wedge 1 \right) \\ \quad \times \left(t^{-d/2} e^{-|x-y|^2/(c_{10}t)} + \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) & \text{for } t \in (3t_0, t_0 a^{-2\alpha/(2-\alpha)}], \\ (1 \wedge \delta_D(x)) \left(\frac{\delta_{\mathbb{H}-b/2}(x_0) \wedge (a^{-1} \delta_{\mathbb{H}-b/2}(x_0))^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) (1 \wedge \delta_D(y)) \\ \quad \times \left(\frac{\delta_{\mathbb{H}-b/2}(y_0) \wedge (a^{-1} \delta_{\mathbb{H}-b/2}(y_0))^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) & \text{for } t > t_0/a^{2\alpha/(2-\alpha)} \end{cases} \\
&\leq c_{11} \begin{cases} (1 \wedge \delta_D(x)) \left(\frac{\delta_{\mathbb{H}}(x_0)}{\sqrt{t}} \wedge 1 \right) (1 \wedge \delta_D(y)) \left(\frac{\delta_{\mathbb{H}}(y_0)}{\sqrt{t}} \wedge 1 \right) \\ \quad \times \left(t^{-d/2} e^{-|x-y|^2/(c_{10}t)} + \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) & \text{for } t \in (3t_0, t_0 a^{-2\alpha/(2-\alpha)}]; \\ (1 \wedge \delta_D(x)) \left(\frac{\delta_{\mathbb{H}}(x_0) \wedge (a^{-1} \delta_{\mathbb{H}}(x_0))^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) (1 \wedge \delta_D(y)) \\ \quad \times \left(\frac{\delta_{\mathbb{H}}(y_0) \wedge (a^{-1} \delta_{\mathbb{H}}(y_0))^{\alpha/2}}{\sqrt{t}} \wedge 1 \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x-y|^{d+\alpha}} \right) & \text{for } t > t_0/a^{2\alpha/(2-\alpha)}. \end{cases}
\end{aligned}$$

In the case when $t > M^{2\alpha/(2-\alpha)} t_0 a^{2\alpha/(\alpha-2)}$, since $M^{2\alpha/(2-\alpha)} t_0 a^{2\alpha/(\alpha-2)} \geq t_0$, the desired result follows from (5.1), Lemma 1.11, Theorem 5.1 and Remark 1.5(ii). In the case when $3t_0 < t \leq M^{2\alpha/(2-\alpha)} t_0 a^{2\alpha/(\alpha-2)}$, the desired upper bound follows from (5.1), Theorem 5.1, Remark 1.5(ii) and [11, Lemma 2.2] (with α there replaced by 2).

The lower bound can be proved similarly. We omit the details. \square

6 Green function estimates

In this section, we give the full proof of Theorem 1.7. Throughout this section, D is a fixed half-space-like $C^{1,1}$ domain with $C^{1,1}$ characteristics (R_0, Λ_0) and $\mathbb{H}_b \subset D \subset \mathbb{H}$ for some $b > 0$ such that the path distance in D is comparable to the Euclidean distance with characteristic λ_0 . We first establish a few lemmas.

Recall that $\phi_a(r) = r \wedge (r/a)^{\alpha/2}$. When $a = 1$, we simply denote ϕ_1 by ϕ ; that is, $\phi(r) = r \wedge r^{\alpha/2}$.

Lemma 6.1 *For every $r \in (0, 1]$ and every open subset U of \mathbb{R}^d ,*

$$\frac{1}{2} \left(1 \wedge \frac{r^2 \phi(\delta_U(x)) \phi(\delta_U(y))}{|x-y|^\alpha} \right) \leq \left(1 \wedge \frac{r \phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{r \phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) \leq 1 \wedge \frac{r^2 \phi(\delta_U(x)) \phi(\delta_U(y))}{|x-y|^\alpha}. \quad (6.1)$$

Proof. The second inequality holds trivially. Without loss of generality, we assume $\delta_U(x) \leq \delta_U(y)$. If both $\frac{r \phi(\delta_U(x))}{|x-y|^{\alpha/2}}$ and $\frac{r \phi(\delta_U(y))}{|x-y|^{\alpha/2}}$ are less than 1 or if both are large than one,

$$\left(1 \wedge \frac{r \phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{r \phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) = 1 \wedge \frac{r^2 \phi(\delta_U(x)) \phi(\delta_U(y))}{|x-y|^\alpha}.$$

So we only need to consider the case when $\frac{r \phi(\delta_U(x))}{|x-y|^{\alpha/2}} \leq 1 < \frac{r \phi(\delta_U(y))}{|x-y|^{\alpha/2}}$. Note that $\phi(\delta_U(y)) \leq \phi(\delta_U(x) + |x-y|)$. If $\delta_U(x) \geq |x-y|$, then $\phi(\delta_U(y)) \leq \phi(2\delta_U(x)) \leq 2\phi(\delta_U(x))$ and so

$$1 \wedge \frac{r^2 \phi(\delta_U(x)) \phi(\delta_U(y))}{|x-y|^\alpha} \leq 1 \wedge 2 \left(\frac{r \phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right)^2 \leq 2 \left(1 \wedge \frac{r \phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right).$$

When $\delta_U(x) < |x - y|$, then $\phi(\delta_U(y)) \leq \phi(2|x - y|) \leq 2|x - y|^{\alpha/2}$ and so

$$1 \wedge \frac{r^2 \phi(\delta_U(x)) \phi(\delta_U(y))}{|x - y|^\alpha} \leq 1 \wedge \frac{2r^2 \phi(\delta_U(x)) |x - y|^{\alpha/2}}{|x - y|^\alpha} \leq 2 \left(1 \wedge \frac{r \phi(\delta_U(x))}{|x - y|^{\alpha/2}} \right)$$

where the assumption $r \leq 1$ is used in the last inequality. This establishes the first inequality of (6.1). \square

For every open subset U of \mathbb{R}^d and $a > 0$, let

$$q_U^a(t, x, y) := \left(1 \wedge \frac{\phi_a(\delta_U(x))}{\sqrt{t}} \right) \left(1 \wedge \frac{\phi_a(\delta_U(y))}{\sqrt{t}} \right) \left((a^\alpha t)^{-d/\alpha} \wedge \frac{a^\alpha t}{|x - y|^{d+\alpha}} \right). \quad (6.2)$$

The following lemma is a direct consequence of (the proof of) Proposition 1.2, Theorem 1.4 and Remark 1.5(ii).

Lemma 6.2 *For every positive constants c_1, c_2 , there exists $c_3 = c_3(c_1, c_2) > 1$ such that for every $a > 0$, $t \leq c_1 a^{-2\alpha/(2-\alpha)}$, every open subset U of \mathbb{R}^d and $x, y \in U$ with $|x - y| \geq a^{-\alpha/(2-\alpha)}$,*

$$c_3^{-1} \left(1 \wedge \frac{\delta_U(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_U(y)}{\sqrt{t}} \right) h_{c_2}^a(t, x, y) \leq q_U^a(t, x, y) \leq c_3 \left(1 \wedge \frac{\delta_U(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_U(y)}{\sqrt{t}} \right) h_{c_2}^a(t, x, y). \quad (6.3)$$

Under the assumption of Theorem 1.3, there is a constant $c = c(M, R_0, \Lambda_0, \lambda_0, \alpha, b) \geq 1$ such that

$$c^{-1} q_D^a(t, x, y) \leq p_D^a(t, x, y) \leq c q_D^a(t, x, y)$$

holds for every $a \in (0, M]$, $t < \infty$, $x, y \in D$ with $|x - y| \geq a^{-\alpha/(2-\alpha)}$.

Observe that

$$\phi_a(\delta_D(\lambda x)) = (\lambda \delta_{\lambda^{-1}D}(x)) \wedge (\lambda^{\alpha/2} a^{-\alpha/2} \delta_{\lambda^{-1}D}(x)^{\alpha/2}) \quad \text{for every } \lambda > 0. \quad (6.4)$$

Let $x_a := a^{\alpha/(2-\alpha)} x$, $y_a := a^{\alpha/(2-\alpha)} y$ and $D_a := a^{\alpha/(2-\alpha)} D$. By (6.4),

$$\phi_a(\delta_D(x)) = \phi_a(\delta_D(a^{-\alpha/(2-\alpha)} x_a)) = a^{-\alpha/(2-\alpha)} \phi(\delta_{D_a}(x_a)) \quad (6.5)$$

and so, for every $s > 0$,

$$q_D^a(a^{-2\alpha/(2-\alpha)} s, x, y) = q_D^a(a^{-2\alpha/(2-\alpha)} s, a^{-\alpha/(2-\alpha)} x_a, a^{-\alpha/(2-\alpha)} y_a) = a^{\alpha d/(2-\alpha)} q_{D_a}^1(s, x_a, y_a). \quad (6.6)$$

We recall that $f_D^a(x, y)$ is defined in (1.9).

Lemma 6.3 *For every $d \geq 1$ and $x, y \in D$, $\int_0^\infty q_D^a(t, x, y) dt \asymp f_D^a(x, y)$, where the implicit constants are independent of D .*

Proof. Let U be an arbitrary open subset of \mathbb{R}^d . We first consider the case $a = 1$ and prove the lemma for U . By a change of variable $u = \frac{|x-y|^\alpha}{t}$, we have

$$\int_0^\infty q_U^1(t, x, y) dt$$

$$\begin{aligned}
&= \frac{1}{|x-y|^{d-\alpha}} \left(\int_0^1 + \int_1^\infty \right) \left(u^{(d/\alpha)-2} \wedge u^{-3} \right) \left(1 \wedge \frac{\sqrt{u}\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\sqrt{u}\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) du \\
&=: I + II.
\end{aligned} \tag{6.7}$$

Note that

$$\begin{aligned}
&\frac{1}{2|x-y|^{d-\alpha}} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) \\
&= \frac{1}{|x-y|^{d-\alpha}} \int_1^\infty u^{-3} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) du \\
&\leq II = \frac{1}{|x-y|^{d-\alpha}} \int_1^\infty u^{-2} \left(u^{-1/2} \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(u^{-1/2} \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) du \\
&\leq \frac{1}{|x-y|^{d-\alpha}} \int_1^\infty u^{-2} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) du \\
&= \frac{1}{|x-y|^{d-\alpha}} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right).
\end{aligned} \tag{6.8}$$

(i) Assume $d > \alpha$. Observe that

$$\begin{aligned}
I &\leq \frac{1}{|x-y|^{d-\alpha}} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right) \int_0^1 u^{(d/\alpha)-2} du \\
&\leq \frac{\alpha}{d-\alpha} \frac{1}{|x-y|^{d-\alpha}} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right).
\end{aligned} \tag{6.9}$$

So by (6.7)–(6.9),

$$\int_0^\infty q_U^1(t, x, y) dt \asymp \frac{1}{|x-y|^{d-\alpha}} \left(1 \wedge \frac{\phi(\delta_U(x))}{|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_U(y))}{|x-y|^{\alpha/2}} \right). \tag{6.10}$$

For the rest of the proof, we assume without loss of generality that $\delta_U(x) \leq \delta_U(y)$ and define

$$u_0 := \frac{\phi(\delta_U(x))\phi(\delta_U(y))}{|x-y|^\alpha}.$$

(ii) Now assume $d = \alpha = 1$. We have by Lemma 6.1,

$$\begin{aligned}
I &\asymp \int_0^1 u^{-1} \mathbf{1}_{\{u \geq 1/u_0\}} du + \int_0^1 u_0 \mathbf{1}_{\{u < 1/u_0\}} du \\
&= \log(u_0 \vee 1) + u_0 ((1/u_0) \wedge 1) = \log(u_0 \vee 1) + (u_0 \wedge 1).
\end{aligned} \tag{6.11}$$

Now by Lemma 6.1, (6.7)–(6.8) and (6.11), we have

$$\int_0^\infty q_U^1(t, x, y) dt \asymp \log(u_0 \vee 1) + 1 \wedge u_0 \asymp \log(1 + u_0).$$

(iii) Lastly we consider the case $d = 1 < \alpha < 2$. By Lemma 6.1,

$$I \asymp \frac{1}{|x-y|^{1-\alpha}} \left(\int_0^1 u^{(1/\alpha)-2} \mathbf{1}_{\{u \geq 1/u_0\}} du + \int_0^1 u_0 u^{(1/\alpha)-1} \mathbf{1}_{\{u < 1/u_0\}} du \right)$$

$$= \frac{1}{|x-y|^{1-\alpha}} \left(\frac{\alpha}{\alpha-1} \left((u_0 \vee 1)^{1-(1/\alpha)} - 1 \right) + \alpha u_0 (u_0 \vee 1)^{-1/\alpha} \right).$$

Hence by (6.7)-(6.8), Lemma 6.1 and the last display we have

$$\begin{aligned} & \int_0^\infty q_U^1(t, x, y) dt \\ & \asymp \frac{1}{|x-y|^{1-\alpha}} (1 \wedge u_0) + \frac{1}{|x-y|^{1-\alpha}} \left(\left((u_0 \vee 1)^{1-(1/\alpha)} - 1 \right) + u_0 (u_0 \vee 1)^{-1/\alpha} \right) \\ & \asymp \frac{1}{|x-y|^{1-\alpha}} \left(u_0 \wedge u_0^{1-(1/\alpha)} \right) = \frac{\phi(\delta_U(x))\phi(\delta_U(y))}{|x-y|} \wedge (\phi(\delta_U(x))\phi(\delta_U(y)))^{(\alpha-1)/\alpha}. \end{aligned}$$

Thus we have proved the lemma for any open set U and $a = 1$. For general $a > 0$, we have by (6.5) and (6.6) that

$$\begin{aligned} & \int_0^\infty q_D^a(t, x, y) dt = a^{-2\alpha/(2-\alpha)} \int_0^\infty q_D^a(a^{-2\alpha/(2-\alpha)}s, x, y) ds = a^{\alpha(d-2)/(2-\alpha)} \int_0^\infty q_{D_a}^1(s, x_a, y_a) ds \\ & \asymp a^{\alpha(d-2)/(2-\alpha)} \begin{cases} \frac{1}{|x_a-y_a|^{d-\alpha}} \left(1 \wedge \frac{\phi(\delta_{D_a}(x_a))}{|x_a-y_a|^{\alpha/2}} \right) \left(1 \wedge \frac{\phi(\delta_{D_a}(y_a))}{|x_a-y_a|^{\alpha/2}} \right) & \text{when } d > \alpha, \\ \log \left(1 + \frac{\phi(\delta_{D_a}(x_a))\phi(\delta_{D_a}(y_a))}{|x_a-y_a|^\alpha} \right) & \text{when } d = 1 = \alpha, \\ \frac{\phi(\delta_{D_a}(x_a))\phi(\delta_{D_a}(y_a))}{|x_a-y_a|} \wedge (\phi(\delta_{D_a}(x_a))\phi(\delta_{D_a}(y_a)))^{(\alpha-1)/\alpha} & \text{when } d = 1 < \alpha. \end{cases} \\ & = a^{\alpha(d-2)/(2-\alpha)} \begin{cases} \frac{a^{-(d-\alpha)\alpha/(2-\alpha)}}{|x-y|^{d-\alpha}} \left(1 \wedge \frac{a^{\alpha/(2-\alpha)}\phi_a(\delta_D(x))}{a^{\alpha^2/2(2-\alpha)}|x-y|^{\alpha/2}} \right) \left(1 \wedge \frac{a^{\alpha/(2-\alpha)}\phi_a(\delta_D(y))}{a^{\alpha^2/2(2-\alpha)}|x-y|^{\alpha/2}} \right) & \text{when } d > \alpha, \\ \log \left(1 + \frac{a^2\phi_a(\delta_D(x))\phi_a(\delta_D(y))}{a|x-y|} \right) & \text{when } d = 1 = \alpha, \\ \frac{a^{2\alpha/(2-\alpha)}\phi_a(\delta_D(x))\phi_a(\delta_D(y))}{a^{\alpha/(2-\alpha)}|x-y|} \wedge (a^{2\alpha/(2-\alpha)}\phi_a(\delta_D(x))\phi_a(\delta_D(y)))^{(\alpha-1)/\alpha} & \text{when } d = 1 < \alpha \end{cases} \\ & = f_D^a(x, y). \end{aligned}$$

□

Lemma 6.4 For every $c > 0$, when $|x-y| \leq a^{-\alpha/(2-\alpha)}$,

$$\begin{aligned} & \int_0^{a^{-2\alpha/(2-\alpha)}} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) \left[t^{-d/2} e^{-c\frac{|x-y|^2}{t}} + \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right] dt \\ & \asymp \begin{cases} |x-y|^{2-d} \left(1 \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|^2} \right) & \text{when } d \geq 3, \\ \log(1 + \frac{a^{2\alpha/(\alpha-2)} \wedge (\delta_D(x)\delta_D(y))}{|x-y|^2}) & \text{when } d = 2, \\ a^{\alpha/(\alpha-2)} \wedge (\delta_D(x)\delta_D(y))^{1/2} \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|} & \text{when } d = 1, \end{cases} \end{aligned}$$

where the implicit constant depend only on c, α and d .

Proof. We first consider the case $a = 1$ and assume U is an arbitrary open set and $x, y \in U$ with $|x-y| \leq 1$. Using the change of variables $u = \frac{|x-y|^2}{t}$, we have

$$\int_0^1 \left(1 \wedge \frac{\delta_U(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_U(y)}{\sqrt{t}} \right) \left[t^{-d/2} e^{-c_1\frac{|x-y|^2}{t}} + \left(\frac{t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right] dt$$

$$\begin{aligned}
&= |x-y|^{2-d} \left(\int_{|x-y|^2}^2 + \int_2^\infty \right) \left(1 \wedge \frac{\sqrt{u} \delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{\sqrt{u} \delta_U(y)}{|x-y|} \right) \left[u^{d/2} e^{-c_1 u} + \left(\frac{|x-y|^{2-\alpha}}{u} \wedge u^{d/2} \right) \right] \frac{du}{u^2} \\
&=: I_1 + I_2.
\end{aligned}$$

Note that since $|x-y|^{2-\alpha} \leq 1$, for $u \geq 2$, $\frac{|x-y|^{2-\alpha}}{u} \wedge u^{d/2} = \frac{|x-y|^{2-\alpha}}{u}$. Thus for any $d \geq 1$,

$$\begin{aligned}
I_2 &= |x-y|^{2-d} \int_2^\infty \left(u^{-1/2} \wedge \frac{\delta_U(x)}{|x-y|} \right) \left(u^{-1/2} \wedge \frac{\delta_U(y)}{|x-y|} \right) \left[u^{d/2} e^{-c_1 u} + \frac{|x-y|^{2-\alpha}}{u} \right] \frac{du}{u} \\
&\leq |x-y|^{2-d} \left(1 \wedge \frac{\delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{\delta_U(y)}{|x-y|} \right) \int_2^\infty \left(u^{d/2-1} e^{-c_1 u} + u^{-2} \right) du \\
&\leq c_2 |x-y|^{2-d} \left(1 \wedge \frac{\delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{\delta_U(y)}{|x-y|} \right)
\end{aligned}$$

and

$$\begin{aligned}
I_2 &\geq |x-y|^{2-d} \int_2^\infty \left(1 \wedge \frac{\delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{\delta_U(y)}{|x-y|} \right) \left[u^{d/2} e^{-c_1 u} + \frac{|x-y|^{2-\alpha}}{u} \right] \frac{du}{u^2} \\
&\geq |x-y|^{2-d} \left(1 \wedge \frac{\delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{\delta_U(y)}{|x-y|} \right) \int_2^\infty u^{d/2-2} e^{-c_1 u} du \\
&\geq c_3 |x-y|^{2-d} \left(1 \wedge \frac{\delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{\delta_U(y)}{|x-y|} \right).
\end{aligned}$$

One the other hand, since $|x-y|^{2-\alpha} \leq 1$, if $u \leq 2$, then

$$u^{-2} \left[u^{d/2} e^{-c_1 u} + \left(\frac{|x-y|^{2-\alpha}}{u} \wedge u^{d/2} \right) \right] \asymp u^{d/2-2}.$$

Using this and the fact that for every $r \in (0, 2]$,

$$\left(1 \wedge \frac{r \delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{r \delta_U(y)}{|x-y|} \right) \leq 1 \wedge \frac{r^2 \delta_U(x) \delta_U(y)}{|x-y|^2} \leq 4 \left(1 \wedge \frac{r \delta_U(x)}{|x-y|} \right) \left(1 \wedge \frac{r \delta_U(y)}{|x-y|} \right), \quad (6.12)$$

we have

$$I_1 \asymp |x-y|^{2-d} \int_{|x-y|^2}^2 \left(1 \wedge \frac{u \delta_U(x) \delta_U(y)}{|x-y|^2} \right) u^{d/2-2} du.$$

Let $u_0 := \frac{\delta_U(x) \delta_U(y)}{|x-y|^2}$.

(i) When $d \geq 3$, it is easy to see that $I_1 \leq |x-y|^{2-d} (1 \wedge u_0)$.

(ii) Assume $d = 2$. We deal with three cases separately.

(a) $u_0 \leq 1$: In this case, since $|x-y| \leq 1$, we have $\delta_U(x) \delta_U(y) \leq 1$ and $I_1 \asymp \int_{|x-y|^2}^2 u_0 du \asymp u_0 \asymp \ln(1 + u_0)$.

(b) $u_0 > 1$ and $|x-y|^2 \leq 1/u_0$: In this case we have $\delta_U(x) \delta_U(y) \leq 1$ and

$$\begin{aligned}
I_1 &\asymp \int_{|x-y|^2}^{u_0^{-1}} u_0 du + \int_{u_0^{-1}}^2 u^{-1} du = u_0(u_0^{-1} - |x-y|^2) + \ln 2 + \ln u_0 \\
&= (1 - u_0 |x-y|^2) + \ln 2 + \ln u_0 \asymp \ln(1 + u_0).
\end{aligned}$$

(c) $u_0 > 1$ and $|x - y|^2 > 1/u_0$: In this case we have $\delta_U(x)\delta_U(y) \geq 1$ and

$$I_1 \asymp \int_{|x-y|^2}^2 u^{-1} du = \ln 2 + \ln |x - y|^{-2} \asymp \ln(1 + |x - y|^{-2}) = \ln \left(1 + \frac{1 \wedge (\delta_U(x)\delta_U(y))}{|x - y|^2} \right).$$

(iii) Now we consider the case $d = 1$. We again deal with three cases separately.

(a) $u_0 \leq 1$. In this case we have

$$I_1 \asymp |x - y| \int_{|x-y|^2}^2 u_0 u^{-1/2} du \asymp |x - y| u_0 (\sqrt{2} - |x - y|) \asymp |x - y| u_0.$$

(b) $u_0 > 1$ and $|x - y|^2 \leq 1/u_0$. In this case we have

$$\begin{aligned} I_1 &\asymp |x - y| \int_{|x-y|^2}^{u_0^{-1}} u_0 u^{-1/2} du + |x - y| \int_{u_0^{-1}}^2 u^{-3/2} du \\ &\asymp u_0 |x - y| (u_0^{-1/2} - |x - y|) + |x - y| (u_0^{1/2} - 2^{-1/2}) \asymp |x - y| u_0^{1/2}. \end{aligned}$$

(c) $u_0 > 1$ and $|x - y|^2 > 1/u_0$. In this case we have

$$I_1 \asymp |x - y| \int_{|x-y|^2}^2 u^{-3/2} du \asymp |x - y| (|x - y|^{-1} - 2^{-1/2}) \asymp 1 - 2^{-1/2} |x - y| \asymp 1.$$

So we have

$$I_1 + I_2 \asymp \begin{cases} |x - y|^{2-d} \left(1 \wedge \frac{\delta_U(x)\delta_U(y)}{|x-y|^2} \right) & \text{when } d \geq 3, \\ \log(1 + \frac{1 \wedge (\delta_U(x)\delta_U(y))}{|x-y|^2}) & \text{when } d = 2, \\ 1 \wedge (\delta_U(x)\delta_U(y))^{1/2} \wedge \frac{\delta_U(x)\delta_U(y)}{|x-y|} & \text{when } d = 1. \end{cases} \quad (6.13)$$

Thus we have proved the lemma for any open set U and $a = 1$. For general $a > 0$, we have by (6.5), (6.6) and (6.13),

$$\begin{aligned} &\int_0^{a^{-2\alpha/(2-\alpha)}} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) \left[t^{-d/2} e^{-c_1 \frac{|x-y|^2}{t}} + \left(\frac{a^\alpha t}{|x-y|^{d+\alpha}} \wedge t^{-d/2} \right) \right] dt \\ &= a^{-2\alpha/(2-\alpha)} \int_0^1 \left(1 \wedge \frac{\delta_D(x)}{a^{-\alpha/(2-\alpha)} \sqrt{s}} \right) \left(1 \wedge \frac{\delta_D(y)}{a^{-\alpha/(2-\alpha)} \sqrt{s}} \right) \\ &\quad \times \left[(a^{-2\alpha/(2-\alpha)} s)^{-d/2} e^{-c_1 \frac{|x-y|^2}{a^{-2\alpha/(2-\alpha)} s}} + \left(\frac{a^\alpha a^{-2\alpha/(2-\alpha)} s}{|x-y|^{d+\alpha}} \wedge (a^{-2\alpha/(2-\alpha)} s)^{-d/2} \right) \right] ds \\ &= a^{\alpha(d-2)/(2-\alpha)} \int_0^1 \left(1 \wedge \frac{\delta_{D_a}(x_a)}{\sqrt{s}} \right) \left(1 \wedge \frac{\delta_{D_a}(y_a)}{\sqrt{s}} \right) \left[s^{-d/2} e^{-c_1 \frac{|x_a-y_a|^2}{s}} + \left(\frac{s}{|x_a-y_a|^{d+\alpha}} \wedge s^{-d/2} \right) \right] ds \\ &\asymp a^{\alpha(d-2)/(2-\alpha)} \begin{cases} |x_a - y_a|^{2-d} \left(1 \wedge \frac{\delta_{D_a}(x_a)\delta_{D_a}(y_a)}{|x_a-y_a|^2} \right) & \text{when } d \geq 3, \\ \log(1 + \frac{1 \wedge (\delta_{D_a}(x_a)\delta_{D_a}(y_a))}{|x_a-y_a|^2}) & \text{when } d = 2, \\ 1 \wedge (\delta_{D_a}(x_a)\delta_{D_a}(y_a))^{1/2} \wedge \frac{\delta_{D_a}(x_a)\delta_{D_a}(y_a)}{|x_a-y_a|} & \text{when } d = 1 \end{cases} \\ &= \begin{cases} |x - y|^{2-d} \left(1 \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|^2} \right) & \text{when } d \geq 3, \\ \log(1 + \frac{a^{2\alpha/(\alpha-2)} \wedge (\delta_D(x)\delta_D(y))}{|x-y|^2}) & \text{when } d = 2, \\ a^{\alpha/(\alpha-2)} \wedge (\delta_D(x)\delta_D(y))^{1/2} \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|} & \text{when } d = 1. \end{cases} \end{aligned}$$

□

Lemma 6.5 For every $d \geq 2$, there exists $c = c(\alpha, d) > 1$ such that, for every $a > 0$, when $|x - y| \leq a^{-\alpha/(2-\alpha)}$,

$$\int_{a^{-2\alpha/(2-\alpha)}}^{\infty} q_D^a(t, x, y) dt \leq c \left(1 \wedge \frac{\delta_D(x)\delta_D(y)}{|x - y|^2} \right).$$

Proof. We first consider the case $a = 1$ and assume U is an arbitrary open set and $x, y \in U$ with $|x - y| \leq 1$. Let $J := \int_1^{\infty} q_U^1(t, x, y) dt$. By a change of variables $u = \frac{|x-y|^\alpha}{t}$,

$$J = |x - y|^{\alpha-d} \int_0^{|x-y|^\alpha} \left(1 \wedge \frac{\sqrt{u}(\delta_U(x) \wedge \delta_U(x)^{\alpha/2})}{|x - y|^{\alpha/2}} \right) \left(1 \wedge \frac{\sqrt{u}(\delta_U(y) \wedge \delta_U(y)^{\alpha/2})}{|x - y|^{\alpha/2}} \right) (u^{d/\alpha} \wedge u^{-1}) \frac{du}{u^2}. \quad (6.14)$$

Since $|x - y| \leq 1$, for $u \in [0, |x - y|^\alpha]$, $u^{d/\alpha} \wedge u^{-1} = u^{d/\alpha}$. Hence

$$\begin{aligned} J &\leq |x - y|^{\alpha-d} \left(1 \wedge \frac{\delta_U(x) \wedge \delta_U(x)^{\alpha/2}}{|x - y|^{\alpha/2}} \right) \left(1 \wedge \frac{\delta_U(y) \wedge \delta_U(y)^{\alpha/2}}{|x - y|^{\alpha/2}} \right) \int_0^{|x-y|^\alpha} u^{d/\alpha-2} du \\ &= c_1 \left(1 \wedge \frac{\delta_U(x) \wedge \delta_U(x)^{\alpha/2}}{|x - y|^{\alpha/2}} \right) \left(1 \wedge \frac{\delta_U(y) \wedge \delta_U(y)^{\alpha/2}}{|x - y|^{\alpha/2}} \right). \end{aligned}$$

Since $|x - y| \leq |x - y|^{\alpha/2} \leq 1$, we have that $\frac{1}{|x-y|^{\alpha/2}} \leq \frac{1}{|x-y|}$ and so $1 \wedge \frac{\delta_U(x) \wedge \delta_U(x)^{\alpha/2}}{|x-y|^{\alpha/2}} \leq 1 \wedge \frac{\delta_U(x)}{|x-y|}$. Consequently,

$$J \leq c_1 \left(1 \wedge \frac{\delta_U(x)}{|x - y|} \right) \left(1 \wedge \frac{\delta_U(y)}{|x - y|} \right) \leq 2c_1 \left(1 \wedge \frac{\delta_U(x)\delta_U(y)}{|x - y|^2} \right). \quad (6.15)$$

Thus we have proved the lemma for any open set U and $a = 1$. For general $a > 0$, by (6.5), (6.6) and (6.15), we have

$$\begin{aligned} \int_{a^{-2\alpha/(2-\alpha)}}^{\infty} q_D^a(t, x, y) dt &= a^{\alpha(d-2)/(2-\alpha)} \int_1^{\infty} q_{D_a}^1(s, x_a, y_a) ds \\ &\leq 2c_1 a^{\alpha(d-2)/(2-\alpha)} \left(1 \wedge \frac{\delta_{D_a}(x_a)\delta_{D_a}(y_a)}{|x_a - y_a|^2} \right) = 2c_1 \left(1 \wedge \frac{\delta_D(x)\delta_D(y)}{|x - y|^2} \right). \end{aligned}$$

□

Lemma 6.6 For every $c > 0$, when $d = 1$ and $|x - y| \leq a^{-\alpha/(2-\alpha)}$,

$$\begin{aligned} &\int_0^{a^{-2\alpha/(2-\alpha)}} \left(1 \wedge \frac{\delta_D(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_D(y)}{\sqrt{t}} \right) \left(t^{-d/2} e^{-c\frac{|x-y|^2}{t}} + \left(\frac{a^\alpha t}{|x - y|^{d+\alpha}} \wedge t^{-d/2} \right) \right) dt \\ &+ \int_{a^{-2\alpha/(2-\alpha)}}^{\infty} q_D^a(t, x, y) dt \asymp g_D^a(x, y) \end{aligned}$$

where the implicit constant depend only on c and α .

Proof. We first consider the case $a = 1$ and assume U is an arbitrary open set and $x, y \in U$ with $|x - y| \leq 1$. Let $J := \int_1^\infty q_U^1(t, x, y) dt$ and

$$I := \int_0^1 \left(1 \wedge \frac{\delta_U(x)}{\sqrt{t}} \right) \left(1 \wedge \frac{\delta_U(y)}{\sqrt{t}} \right) \left(t^{-1/2} e^{-c_1 \frac{|x-y|^2}{t}} + \left(\frac{t}{|x-y|^{1+\alpha}} \wedge t^{-1/2} \right) \right) dt.$$

By Lemma 6.4, $I \asymp 1 \wedge (\delta_D(x)\delta_D(y))^{1/2} \wedge \frac{\delta_D(x)\delta_D(y)}{|x-y|}$. Using Lemma 6.1 and (6.14), we get that

$$\int_1^\infty q_U^1(t, x, y) dt \asymp |x-y|^{\alpha-1} \int_0^{|x-y|^\alpha} \left(1 \wedge \frac{u\phi(\delta_U(x))\phi(\delta_U(y))}{|x-y|^\alpha} \right) u^{1/\alpha-2} du.$$

Put $u_0 := \frac{\phi(\delta_U(x))\phi(\delta_U(y))}{|x-y|^\alpha}$. Then we have

$$J \asymp |x-y|^{\alpha-1} \left(u_0 \int_0^{|x-y|^\alpha \wedge u_0^{-1}} u^{1/\alpha-1} du + \int_{|x-y|^\alpha \wedge u_0^{-1}}^{|x-y|^\alpha} u^{1/\alpha-2} du \right).$$

Without loss of generality, we assume $\delta_U(x) \leq \delta_U(y)$. Note that, since $|x-y| \leq 1$, if $\delta_U(x) \leq 1$ then $\delta_U(y) \leq 2$, and if $\delta_U(x) > 1$ then $1 < \delta_U(x) \leq \delta_U(y) \leq 2\delta_U(x)$ and $\delta_U(x)\delta_U(y) \geq |x-y|^2$.

Now we look at three separate cases.

(i) $\alpha \in (1, 2)$: In this case we have

$$\begin{aligned} J &\asymp |x-y|^{\alpha-1} \left(\alpha u_0 (|x-y| \wedge u_0^{-1/\alpha}) + \frac{\alpha}{\alpha-1} (|x-y|^\alpha \wedge u_0^{-1})^{(1-\alpha)/\alpha} - \frac{\alpha}{\alpha-1} |x-y|^{1-\alpha} \right) \\ &\asymp \phi(\delta_U(x))\phi(\delta_U(y)) \wedge (\phi(\delta_U(x))\phi(\delta_U(y)))^{(\alpha-1)/\alpha}. \end{aligned}$$

Thus

$$\begin{aligned} I + J &\asymp \begin{cases} (\delta_U(x)\delta_U(y))^{1/2} & \text{when } \delta_U(x) \leq 1, \delta_U(x)\delta_U(y) \geq |x-y|^2, \\ \frac{\delta_U(x)\delta_U(y)}{|x-y|} & \text{when } \delta_U(x) \leq 1, \delta_U(x)\delta_U(y) \leq |x-y|^2, \\ (\delta_U(x)\delta_U(y))^{(\alpha-1)/2} & \text{when } \delta_U(x) > 1 \end{cases} \\ &= (\delta_U(x)\delta_U(y))^{1/2} \wedge (\delta_U(x)\delta_U(y))^{(\alpha-1)/2} \wedge \frac{\delta_U(x)\delta_U(y)}{|x-y|}. \end{aligned}$$

(ii) $\alpha = 1$: In this case we have

$$\begin{aligned} J &\asymp \left(u_0(|x-y| \wedge u_0^{-1}) + \log \frac{|x-y|^\alpha}{|x-y|^\alpha \wedge u_0^{-1}} \right) \\ &\asymp \phi(\delta_U(x))\phi(\delta_U(y)) \wedge 1 + \log(1 \vee \phi(\delta_U(x))\phi(\delta_U(y))) \asymp \log(1 + \phi(\delta_U(x))\phi(\delta_U(y))). \end{aligned}$$

Thus

$$\begin{aligned} I + J &\asymp \begin{cases} (\delta_U(x)\delta_U(y))^{1/2} & \text{when } \delta_U(x) \leq 1, \delta_U(x)\delta_U(y) \geq |x-y|^2, \\ \frac{\delta_U(x)\delta_U(y)}{|x-y|} & \text{when } \delta_U(x) \leq 1, \delta_U(x)\delta_U(y) \leq |x-y|^2, \\ \log(1 + \delta_U(x)\delta_U(y)) & \text{when } \delta_U(x) > 1 \end{cases} \\ &\asymp \frac{\delta_U(x)\delta_U(y)}{|x-y|} \wedge \log(1 + (\delta_U(x)\delta_U(y))^{1/2}). \end{aligned}$$

(iii) $\alpha \in (0, 1)$: In this case (note that $1 - 1/\alpha$ is negative) we have

$$\begin{aligned} J &\asymp |x - y|^{\alpha-1} \left(\alpha u_0(|x - y| \wedge u_0^{-1/\alpha}) + \frac{\alpha}{1 - \alpha} |x - y|^{1-\alpha} - \frac{\alpha}{1 - \alpha} (|x - y|^\alpha \wedge u_0^{-1})^{(1-\alpha)/\alpha} \right) \\ &\asymp \phi(\delta_U(x)) \phi(\delta_U(y)) \wedge 1. \end{aligned}$$

Thus

$$\begin{aligned} I + J &\asymp \begin{cases} (\delta_U(x) \delta_U(y))^{1/2} & \text{when } \delta_U(x) \leq 1, \delta_U(x) \delta_U(y) \geq |x - y|^2, \\ \frac{\delta_U(x) \delta_U(y)}{|x - y|} & \text{when } \delta_U(x) \leq 1, \delta_U(x) \delta_U(y) \leq |x - y|^2, \\ 1 & \text{when } \delta_U(x) > 1 \end{cases} \\ &= (\delta_U(x) \delta_U(y))^{1/2} \wedge \frac{\delta_U(x) \delta_U(y)}{|x - y|} \wedge 1. \end{aligned}$$

Therefore we have proved the lemma for any arbitrary open set U and $a = 1$. The general case $a > 0$ now follows from the same scaling arguments as in the proofs for Lemmas 6.3 and 6.4. \square

Proof of Theorem 1.7. Without loss of generality, we assume $M = b = 1$. Estimates (1.10) follow from Theorem 1.4, Remark 1.5(ii) and Lemmas 6.4–6.6. Estimates (1.11) follow from Theorem 1.4 and Lemmas 6.2 and 6.3. \square

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